# *Electron Beam Pumped Krypton-Fluoride (KrF) Lasers for Fusion Energy*

**A Tutorial**
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*Work proudly sponsored by DOE/NNSA/DP*

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# *Main points of the talk*

## What is a KrF Laser?

Electron beam pumped gas laser

## KrF Lasers for Inertial Fusion Energy

Strengths: Beam uniformity, zooming, cost, scale to large systems

R&D required: efficiency and durability

## The Physics and Technologies of KrF Lasers

Electron beam propagation, transport, and deposition

KrF Kinetics

Pulsed Power

## Phased program to develop a KrF Fusion Driver

Part of an integrated program to develop laser fusion energy

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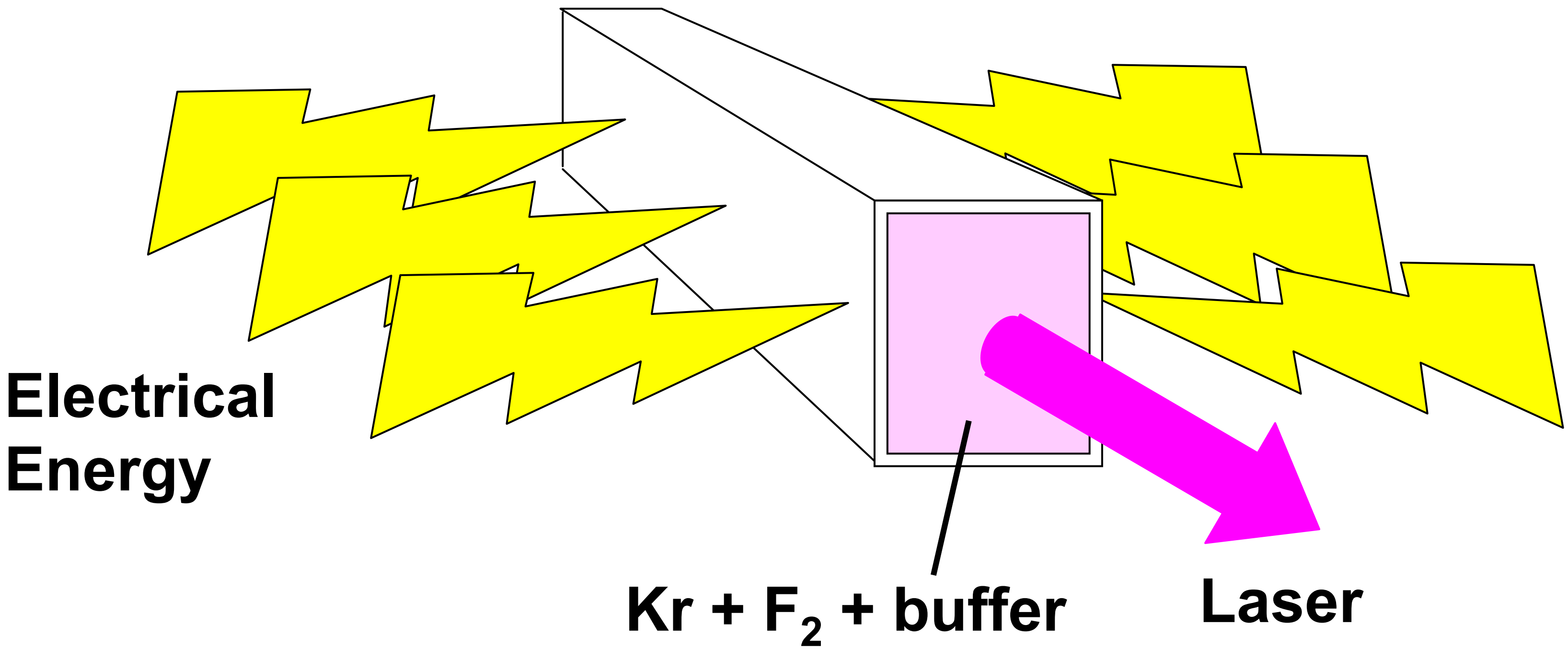
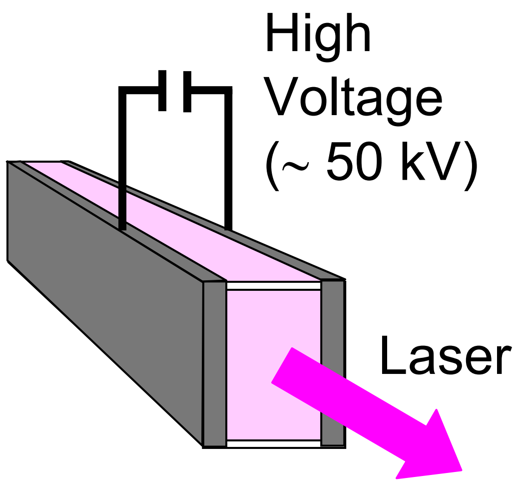
# A Krypton Fluoride (KrF) Laser--- Gas Medium, Electrically Pumped

Energy + ( Kr+ $F_2$) $\Rightarrow$ ( KrF)* + F $\Rightarrow$ Kr + $F_2$ + h$\nu$ ($\lambda$ = 248 nm)



# *Large KrF Lasers are pumped with electron beams*

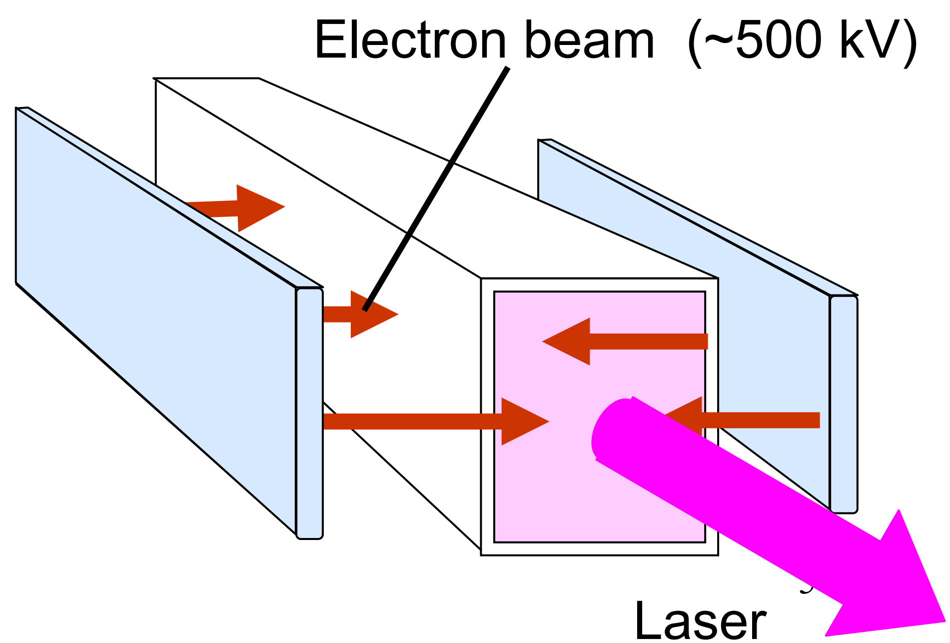
***Small Systems*** (< 1 J, < 10 ns)
(Semiconductor manufacturing)
>> *DISCHARGE PUMPED*





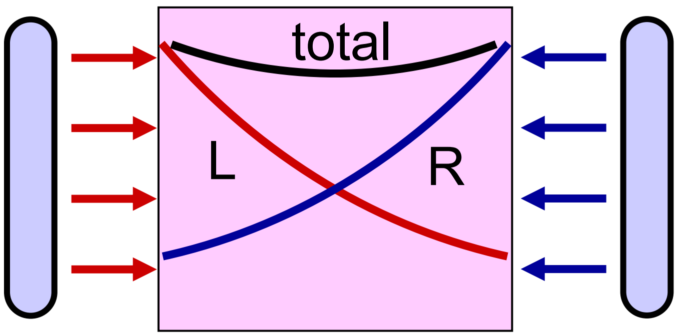
Cymer
NanoLith™ 7000

***Large Systems*** ( 10’s kJ, 100’ ns)
(Fusion Driver)
>> *ELECTRON BEAM PUMPED*



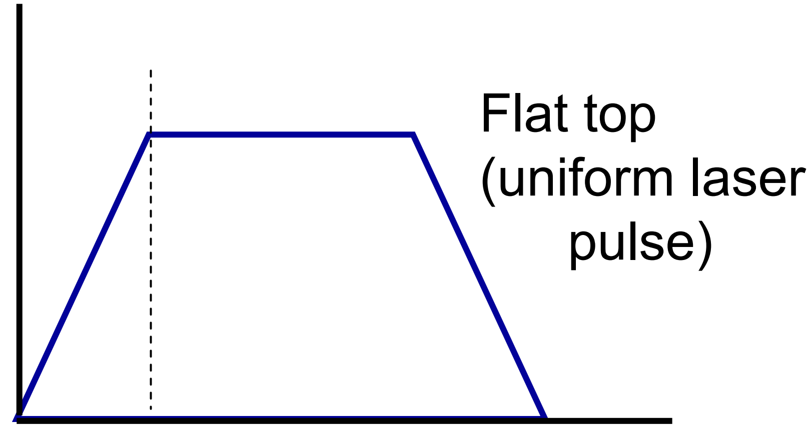
# *E-beam considerations*

Beam Voltage




- Cell length: window size
- Gas pressure: physics + mechanical constraints
- Adjust voltage for uniform energy deposition

Power Waveform




High *Laser Energy* requires high *E-Beam Energy* $= \int_0^{\tau} IVdt$

V $\Rightarrow$ fixed by gas deposition requirements 300-800 kV

I $\Rightarrow$ limited by diode physics (impedance) to > 0.5 to 1.0 V

$\tau \Rightarrow$ limited by diode physics (impedance collapse) to < 1000 nsec

# *The key issues for KrF are being addressed with the Electra and Nike Lasers at NRL*

**Electra:**
> 400 J laser light
500 keV/100 kA/100 nsec
5 Hz; 100,000 shots (5 Hrs)

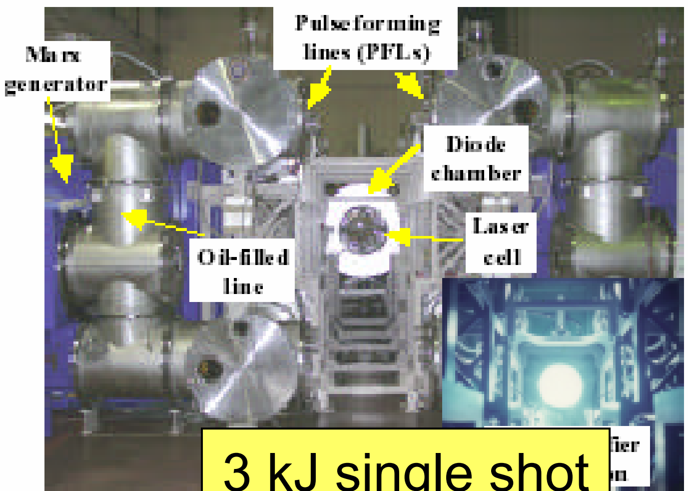
*Develop technologies for:*
*Rep-Rate,*
*Durability,*
*Efficiency,*
*Cost*

**Nike:**
3-5 kJ laser light
750 keV, 500 kA, 240 nsec
single shot

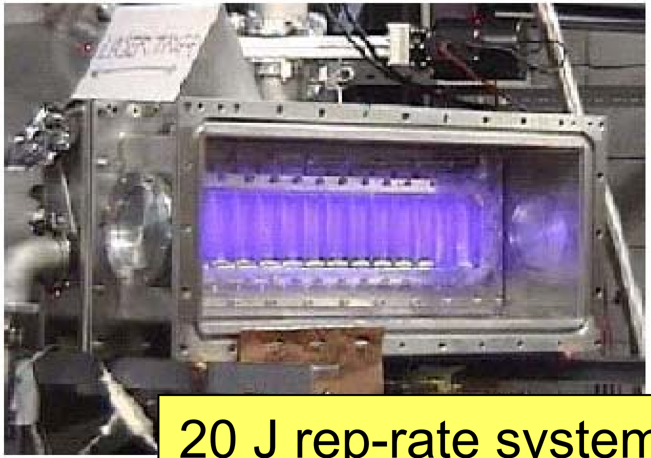
*E-beam physics on full scale diode*
*Laser-target physics*

# Other KrF laser facilities

## ASHURA
(AIST, JAPAN)

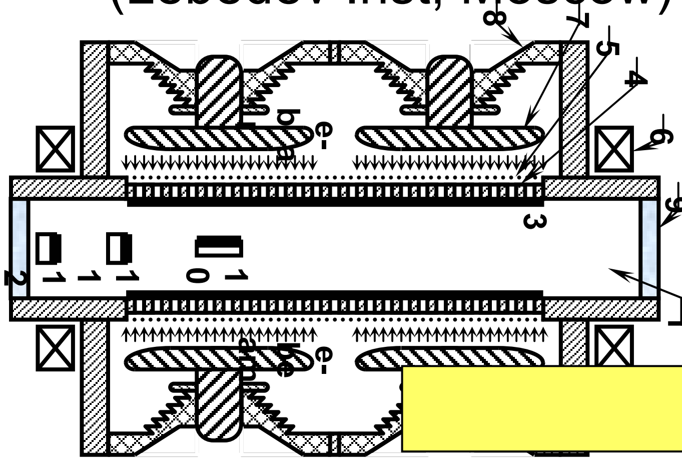



3 kJ single shot

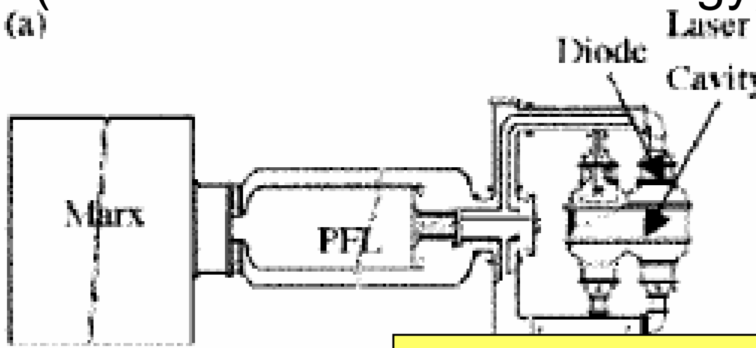


20 J rep-rate system

## GARPUN
(Lebedev Inst, Moscow)

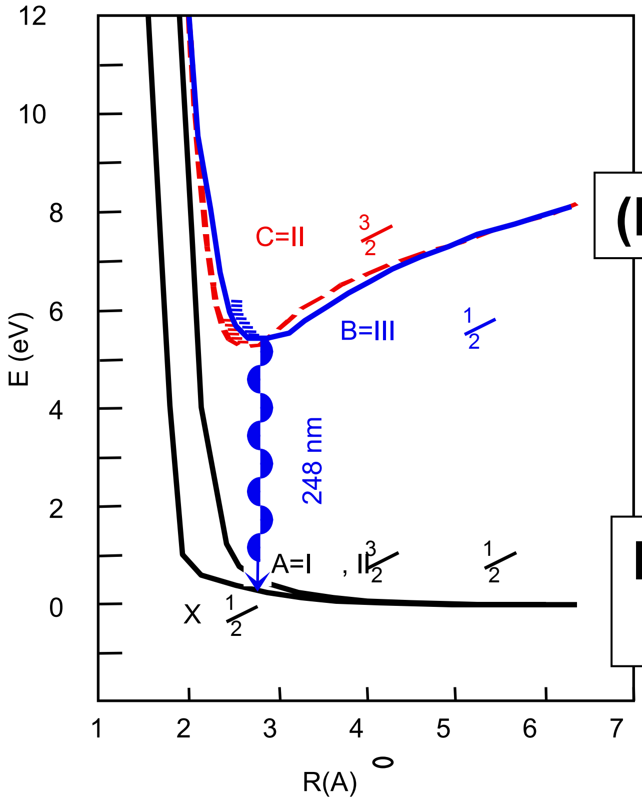


## Heaven-I
(China Institute Atomic Energy)




100J single shot

# KrF is an Excimer (Excited Dimer) laser.
# 1. Molecular electronic transition
# 2. Ground state immediately dissociates



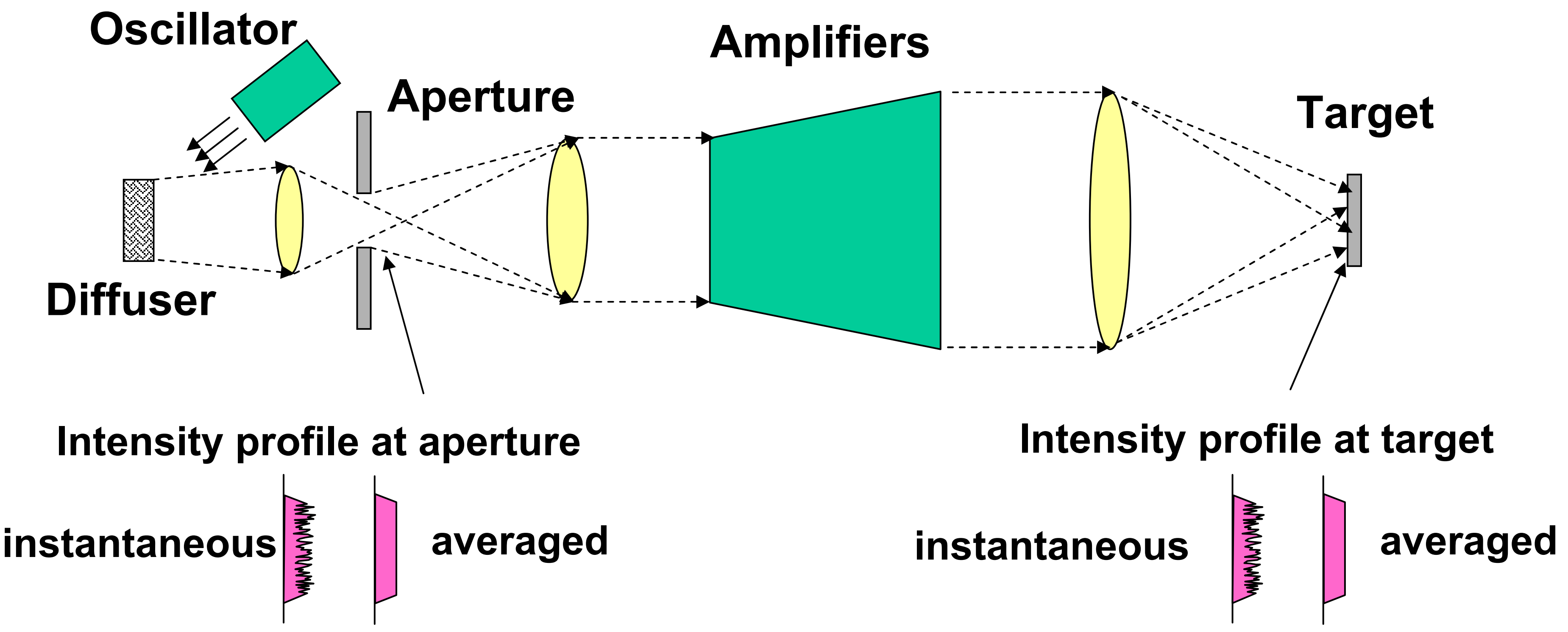

**(KrF)* -- *excited state***

**KrF-- ground state--**
(dissociates as potential is repulsive)

**Two key features of KrF:**

1. Large Bandwidth: 1-3 THz
   no well-defined rotational/vibrational transition
2. Fast relaxation times: ~ 6 nsec

## Large bandwidth of KrF means short averaging times. Hence rapid smoothing of the beam spatial profile. Result: Very uniform illumination of target

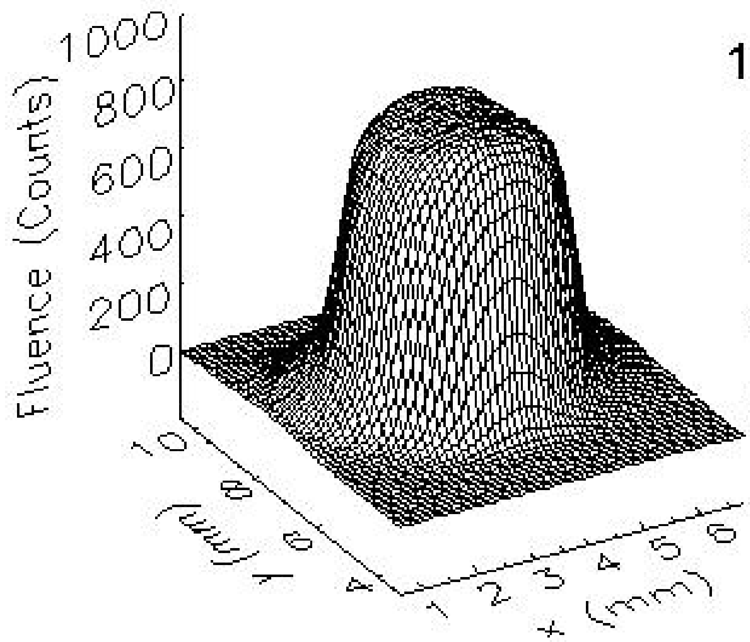


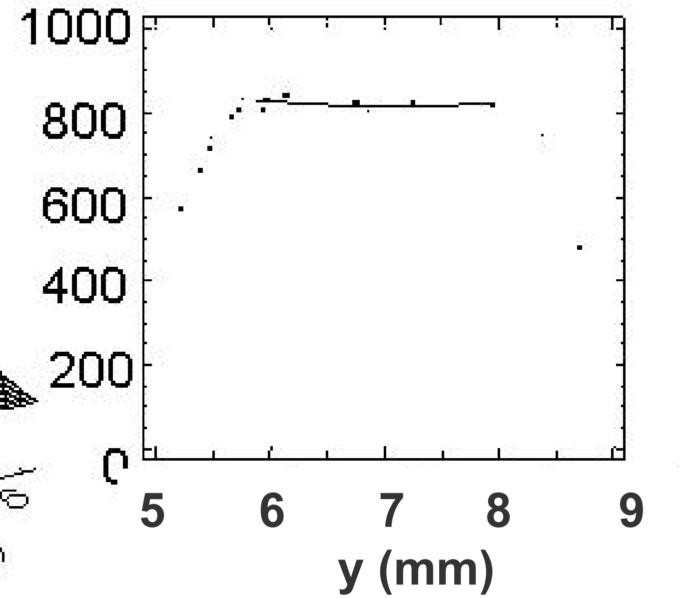

The laser profile at the aperture is imaged through the amplifiers onto the target

If the optical distortion is small, then the image duplicates the aperture

**Concept of *Induced Spatial Incoherence* (ISI)**

# *The NRL Nike KrF Laser (3-5 kJ) produces very uniform focal profiles*




For 50% of the FWHM diameter:

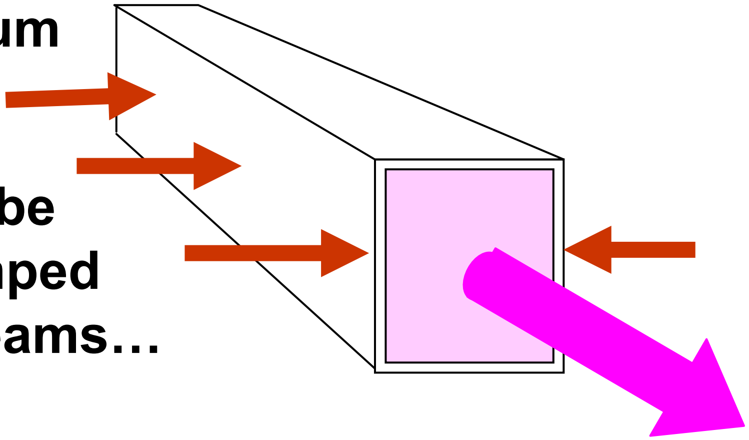
Power tilts < 2%

Quadratic curvature: < 3%

RMS speckle non- uniformity:
0.3 - 1.3% (*all modes*)

## *Time scale miss-match #1:*
## *6 nsec: Relaxation time of (KrF)**
## *vs*
## *100's nsec: E-beam (pulsed power)*
## *Solved by continual pumping and extraction*

**KrF is not a storage medium**



**So Kr +$F_2$ must be continually pumped with electron beams…**

**….while laser energy is continually extracted**

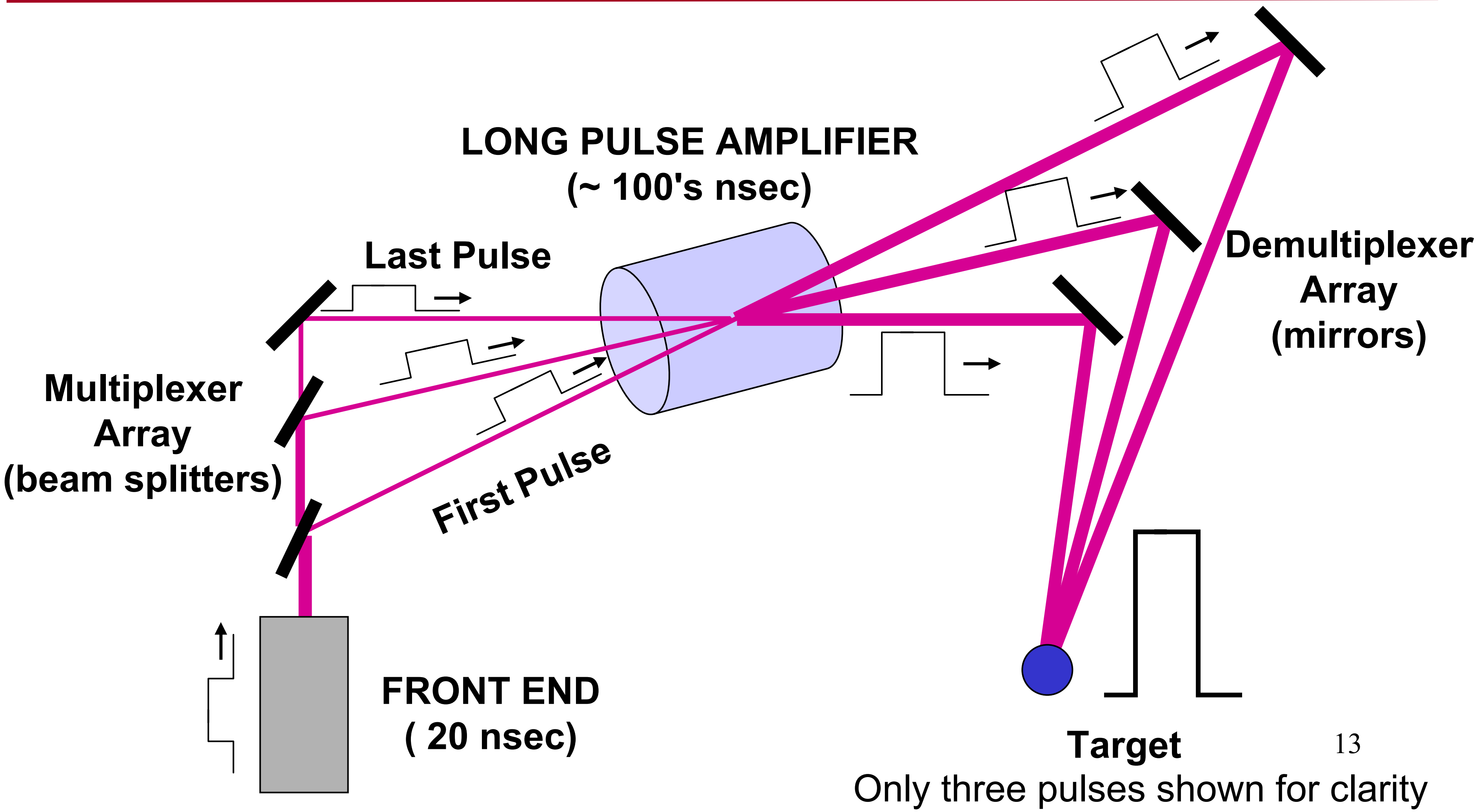
*Timescale miss-match #2:*

*~ 8-16 nsec: Target Physics time scale*

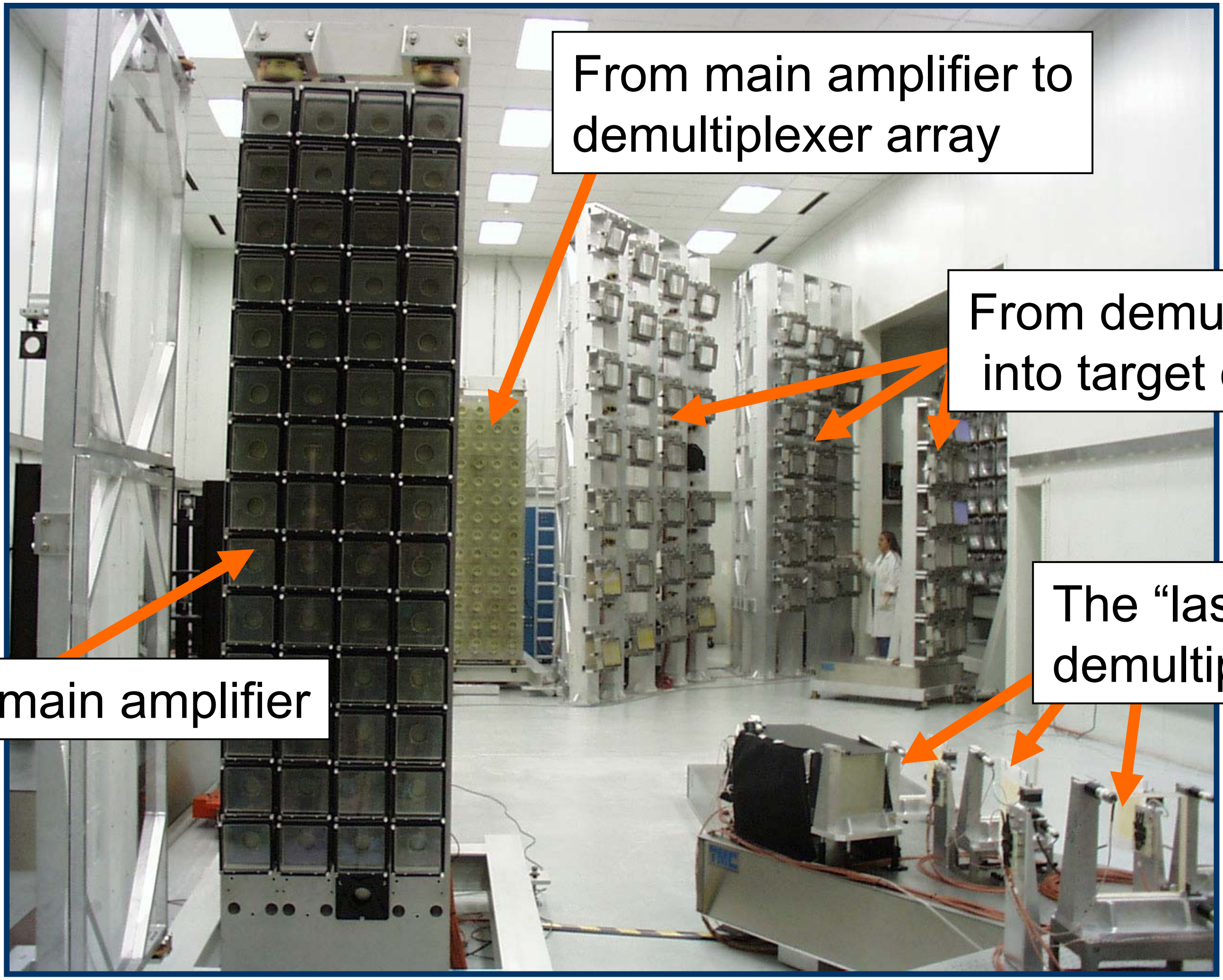
*vs*

*100's nsec: E-beam (pulsed power)*

*Solved by angular multiplexing*



# *The Nike Laser demonstrates routine use of angular multiplexing*



# *Main points of the talk*

## What is a KrF Laser?

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Strengths: Beam uniformity, zooming, cost, scale to large systems

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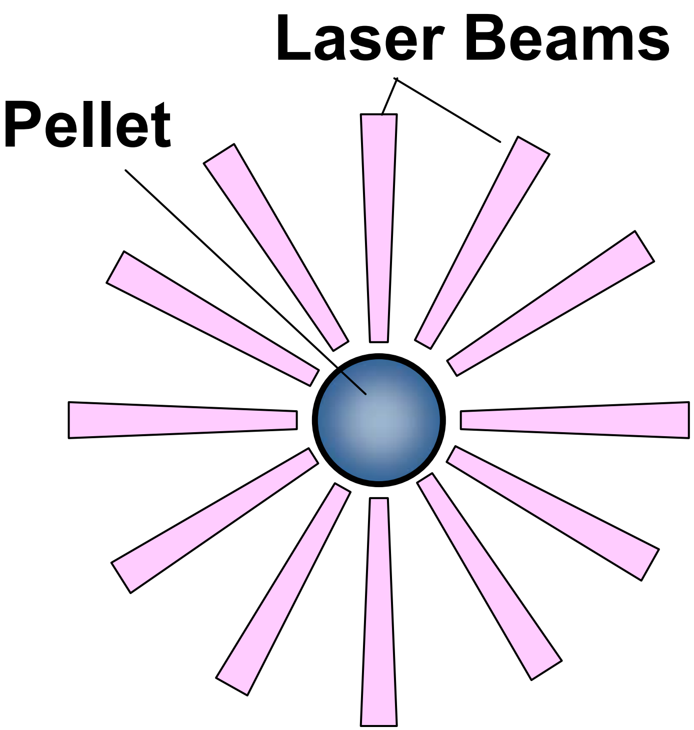
## Phased program to develop a KrF Fusion Driver

Part of an integrated program to develop laser fusion energy

# Direct drive approach to fusion energy




**Just might work!**

-- 1-D gains > 100, 2-D being calculated

**Higher efficiency**

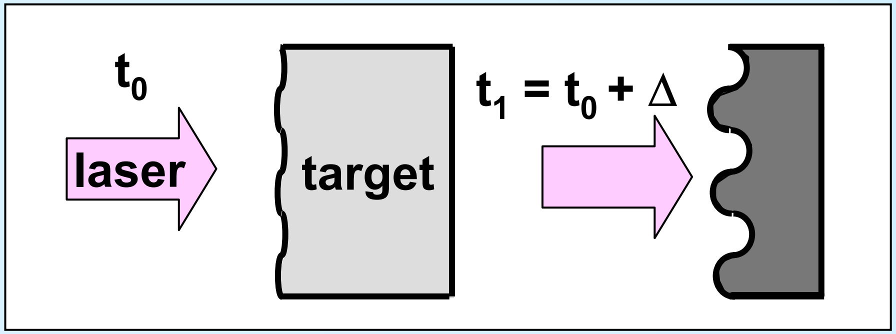
--better coupling of laser to fuel

**Targets relatively simple (cheap) to fabricate--**

--key issue is injection

**Physics is simpler**

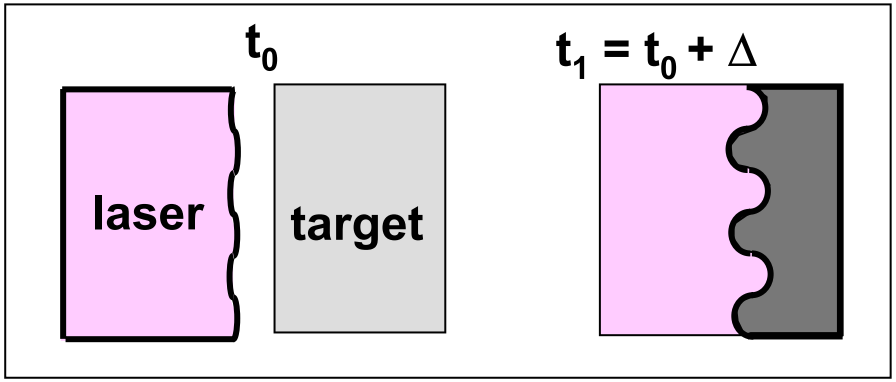
--key issue is hydrodynamic stability

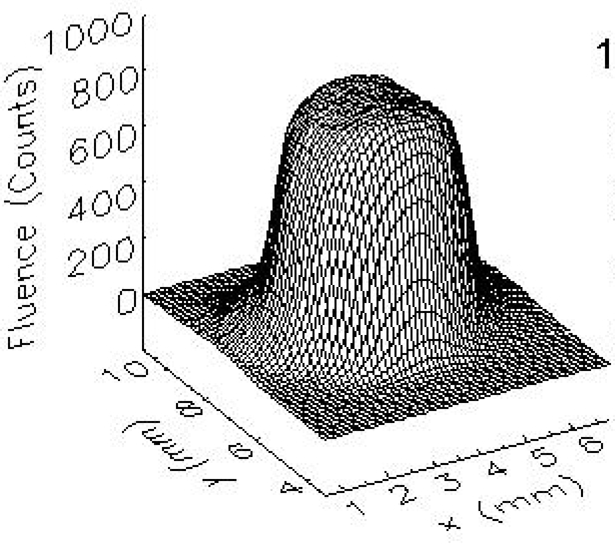


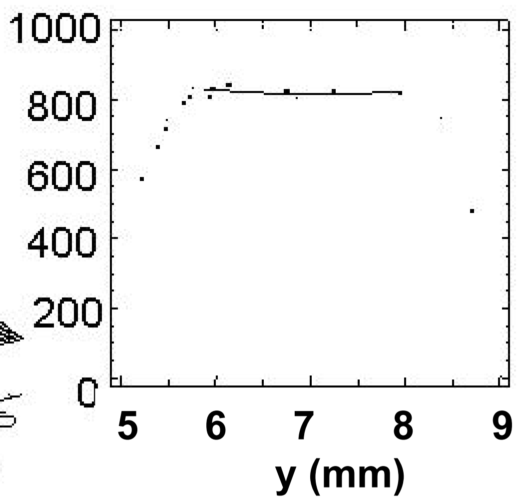
# KrF lasers produce very uniform laser beams
# Reduces "Imprinting" by laser

"Imprinting"--
Modulations imposed on target
due to non-uniformities in laser..

"Seed" for Rayleigh Taylor Instability

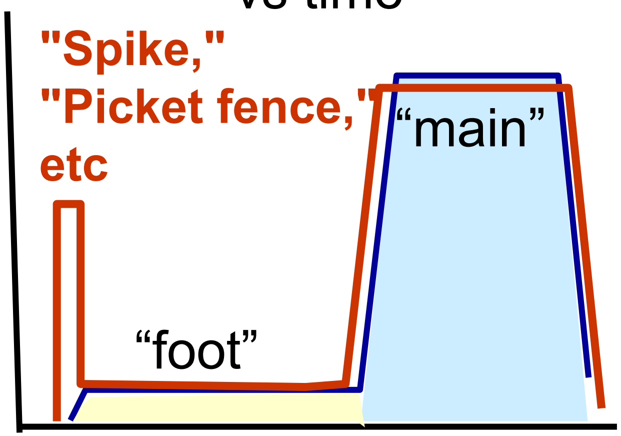


# *Shape laser pulse to help raise ablator isentrope:*

Laser Intensity
vs time

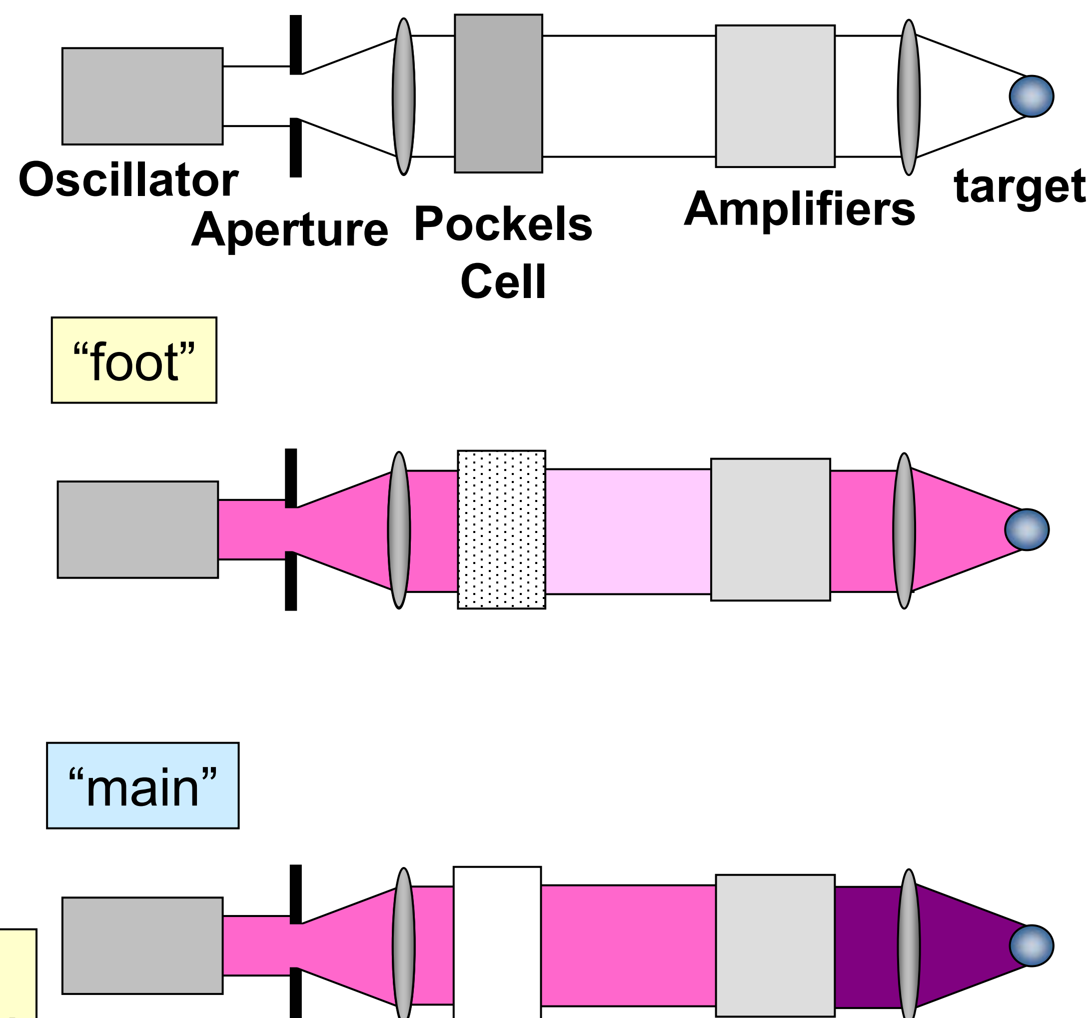



**Low intensity foot launches mild shock through ablator, preheats it to raise isentrope**

**Can accommodate odder pulse shapes**

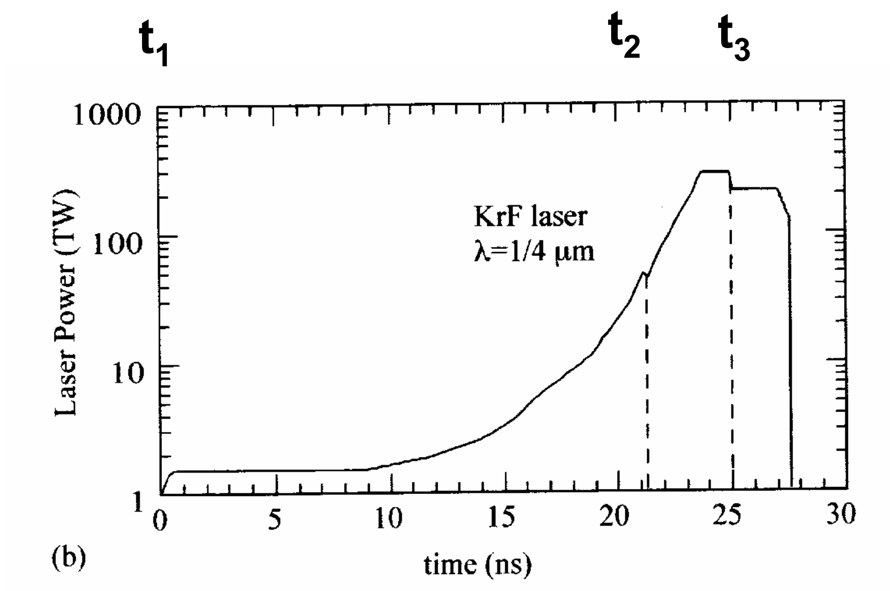
ALL ICF LASERS HAVE
PULSE SHAPING CAPABILITY

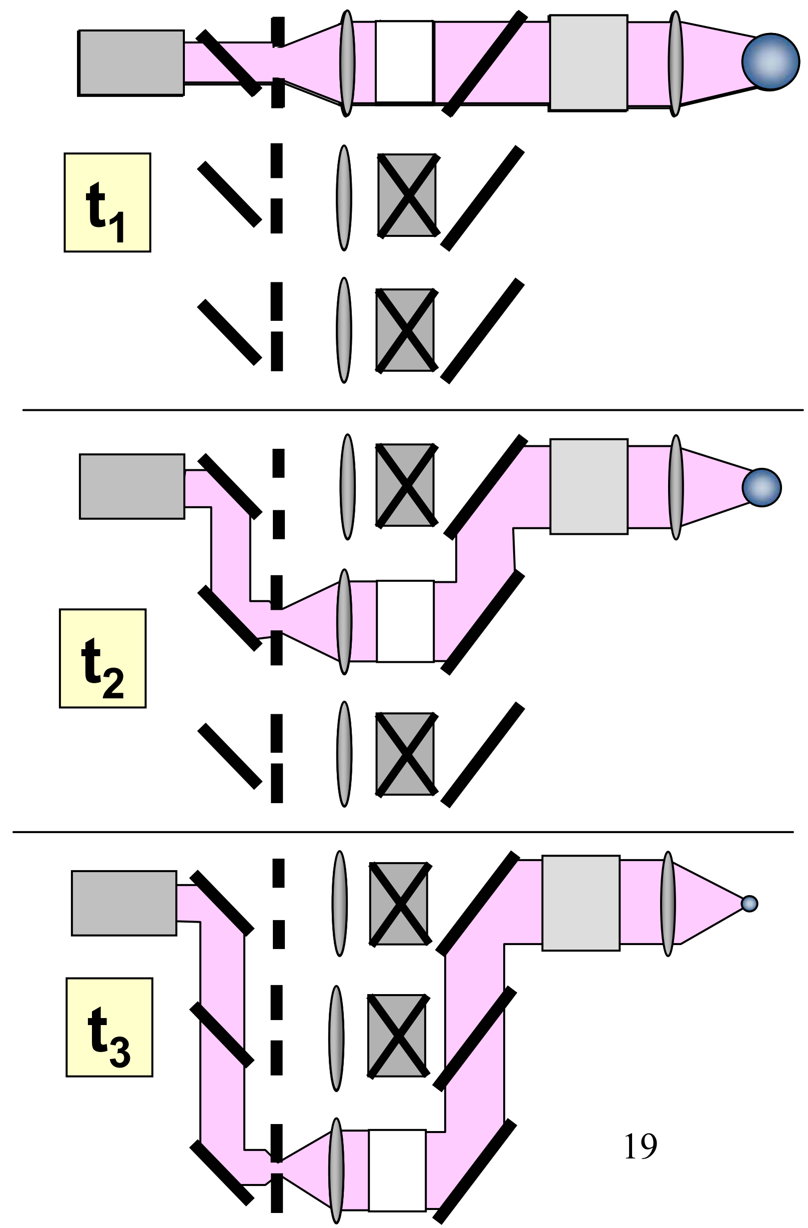
OPTICAL TRAIN OF KrF LASER



# Straightforward with KrF to "Zoom" laser beams. This can boost laser absorption substantially (30%)

Decrease the laser focal spot
to follow the compressing target

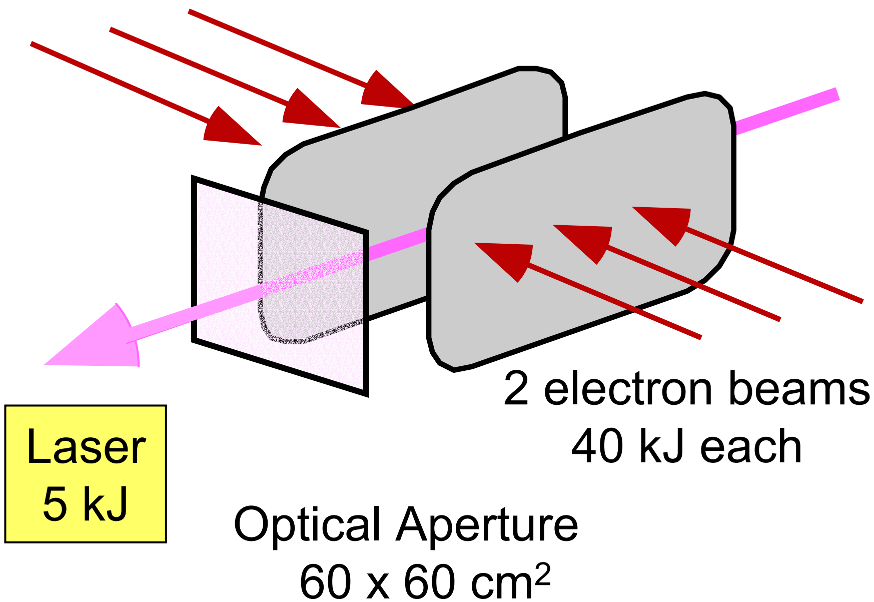


# KrF driver would be modular: 30-40 identical amplifiers
# The amplifiers would be made of modular components

## WHERE WE ARE NOW…..

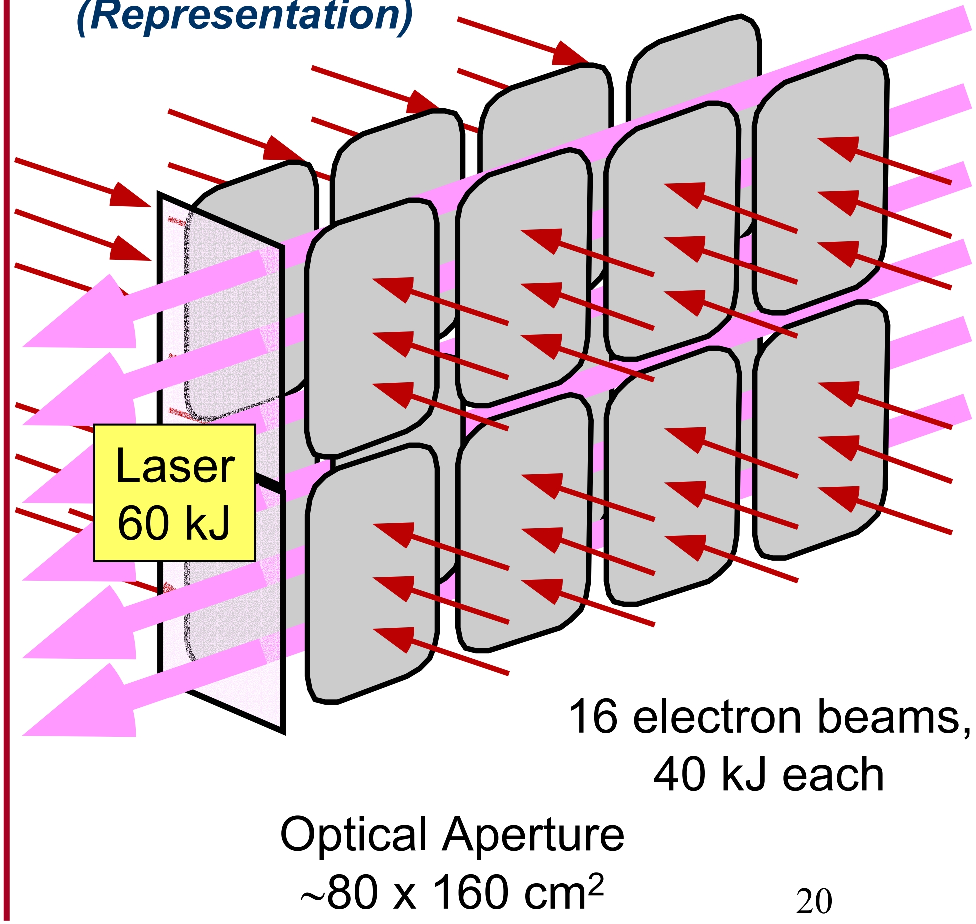
### Nike 60cm Amplifier - 5 kJ output




## WHERE WE WANT TO BE….

### IFE-sized Amplifier- 60 kJ output

**(Representation)**



# *Assessment of KrF lasers for a fusion driver*

## Advantages

**Beam uniformity**

**Simple zoom, pulse shape**

**Modular and scalable;**

Lowers develop costs

**Pulsed power based**

Low cost, industrial technology

## R & D Challenges

**Efficiency:**

12 % Intrinsic KrF
80% Pulsed Power
80% Hibachi
90% Auxiliary
= 7 % total
*(OK for target gain > 100)*

**Durability:**

3 x 10 $^{8}$ shots (5 Hz @ 2 years)

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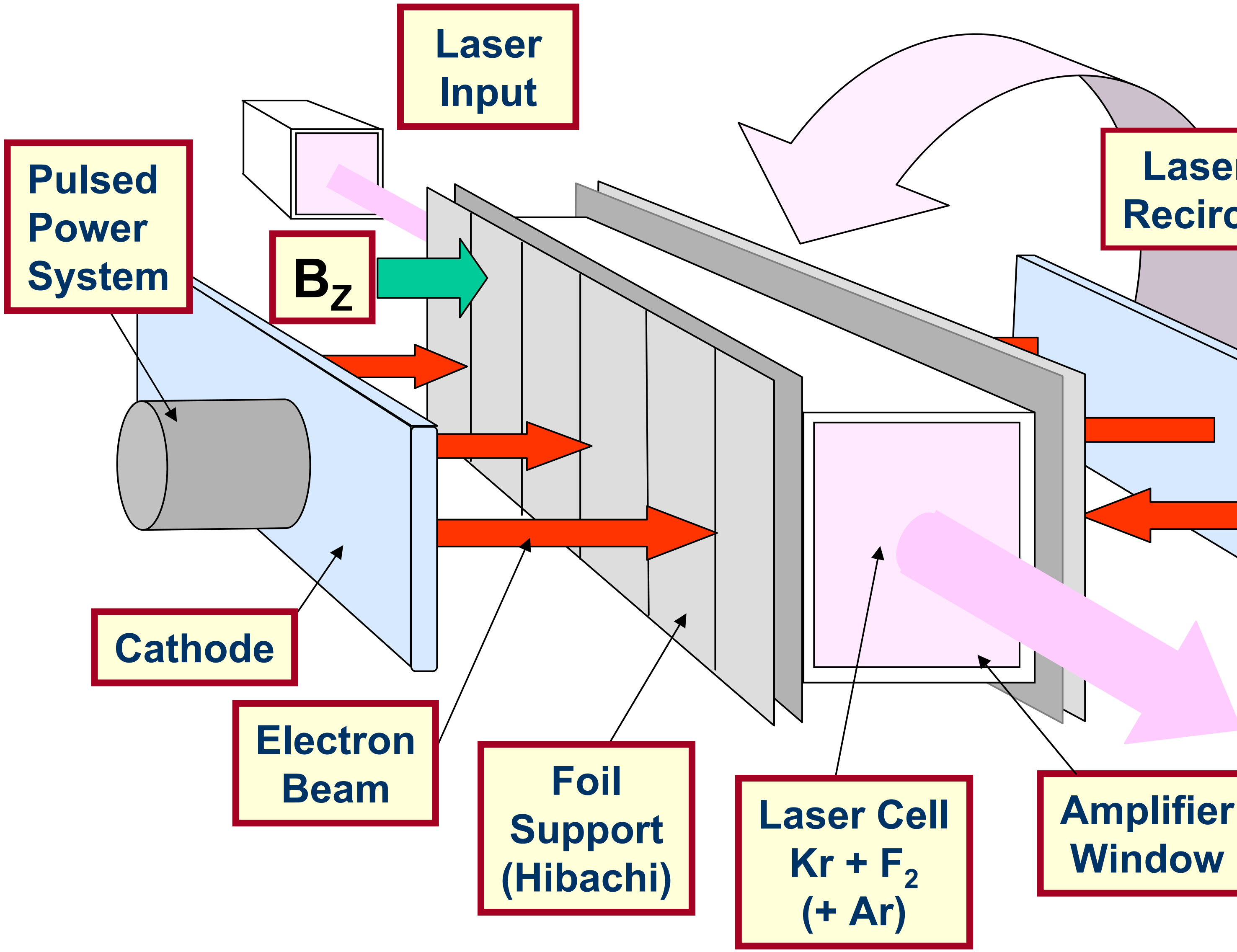
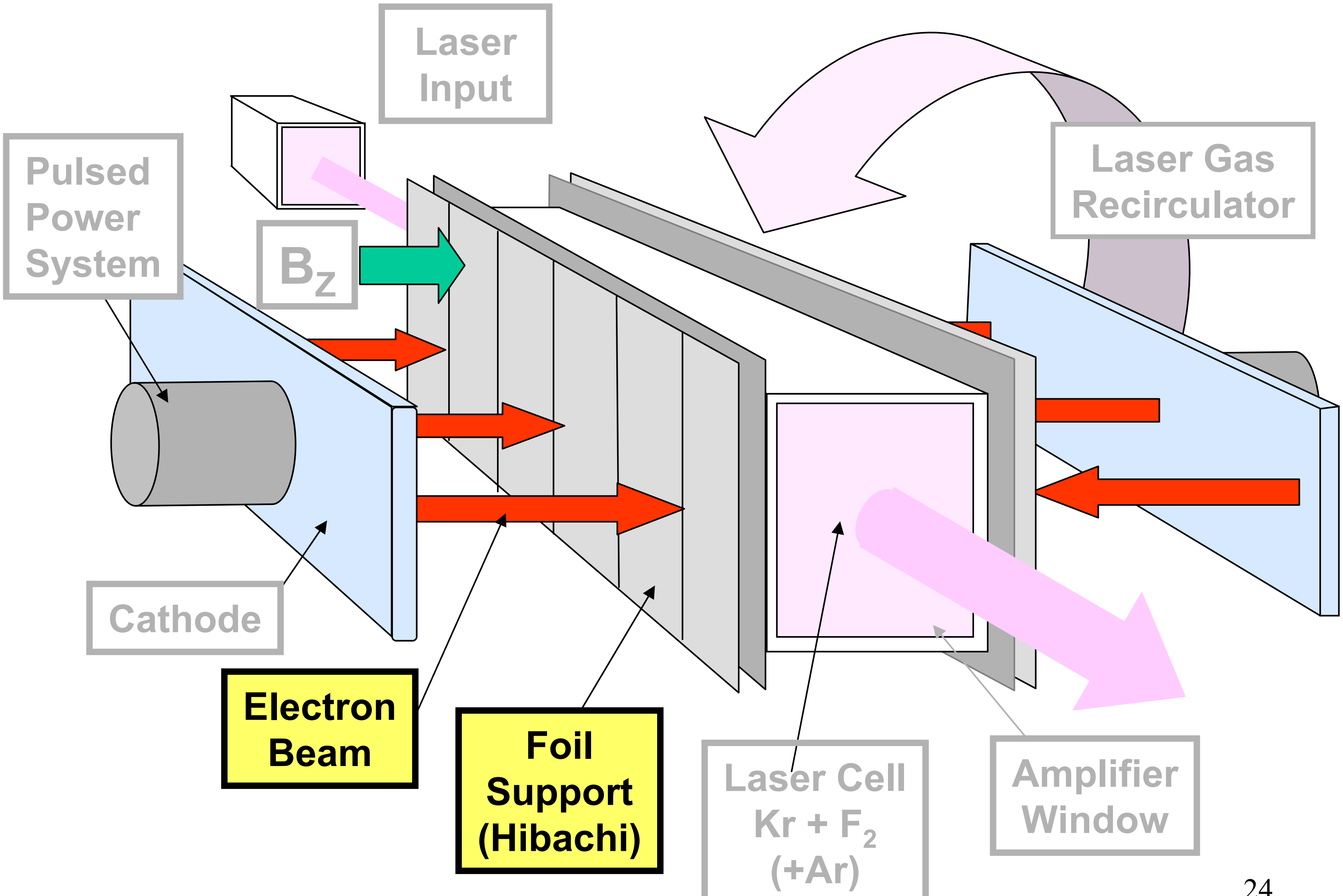
# The key components of a Krypton Fluoride (KrF) Laser

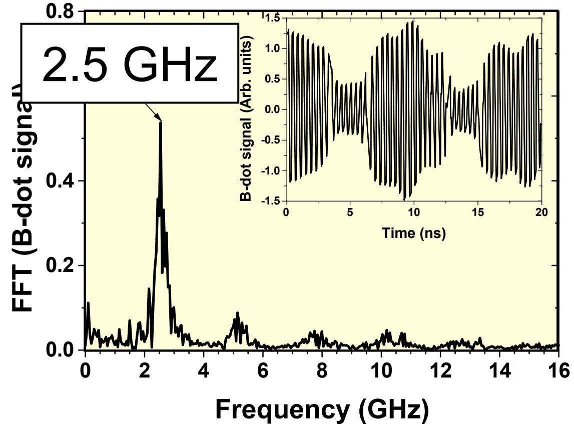


# Electron beam propagation, transport, and deposition

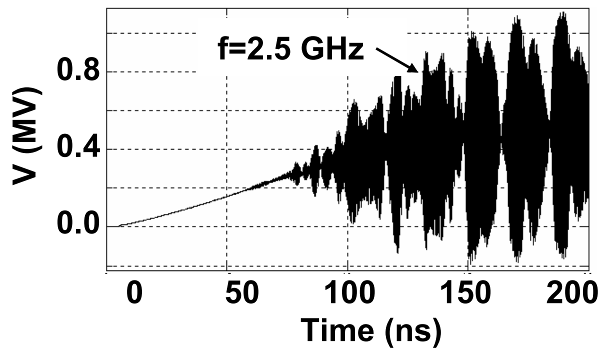


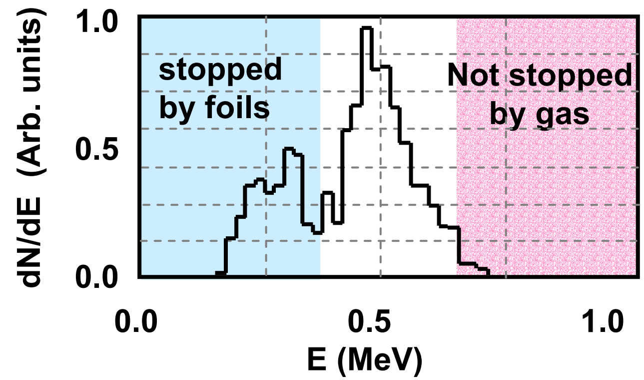
# Experiments and 2-D models show "Transit Time" Instability in large area, low impedance diodes

Experiment (Nike)

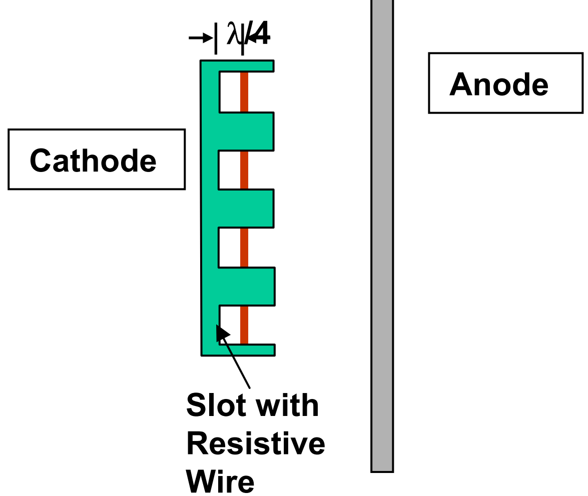


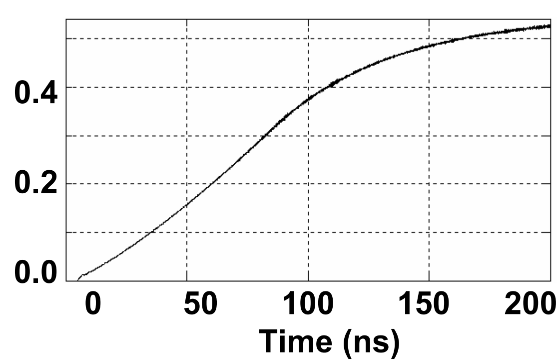

Theory

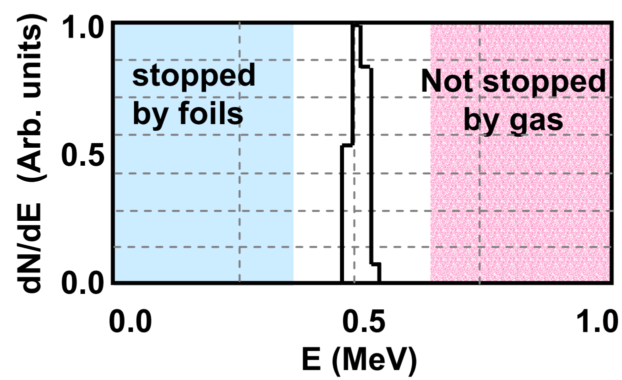



Theory: mitigate instability by adding resistively tuned slots in cathode

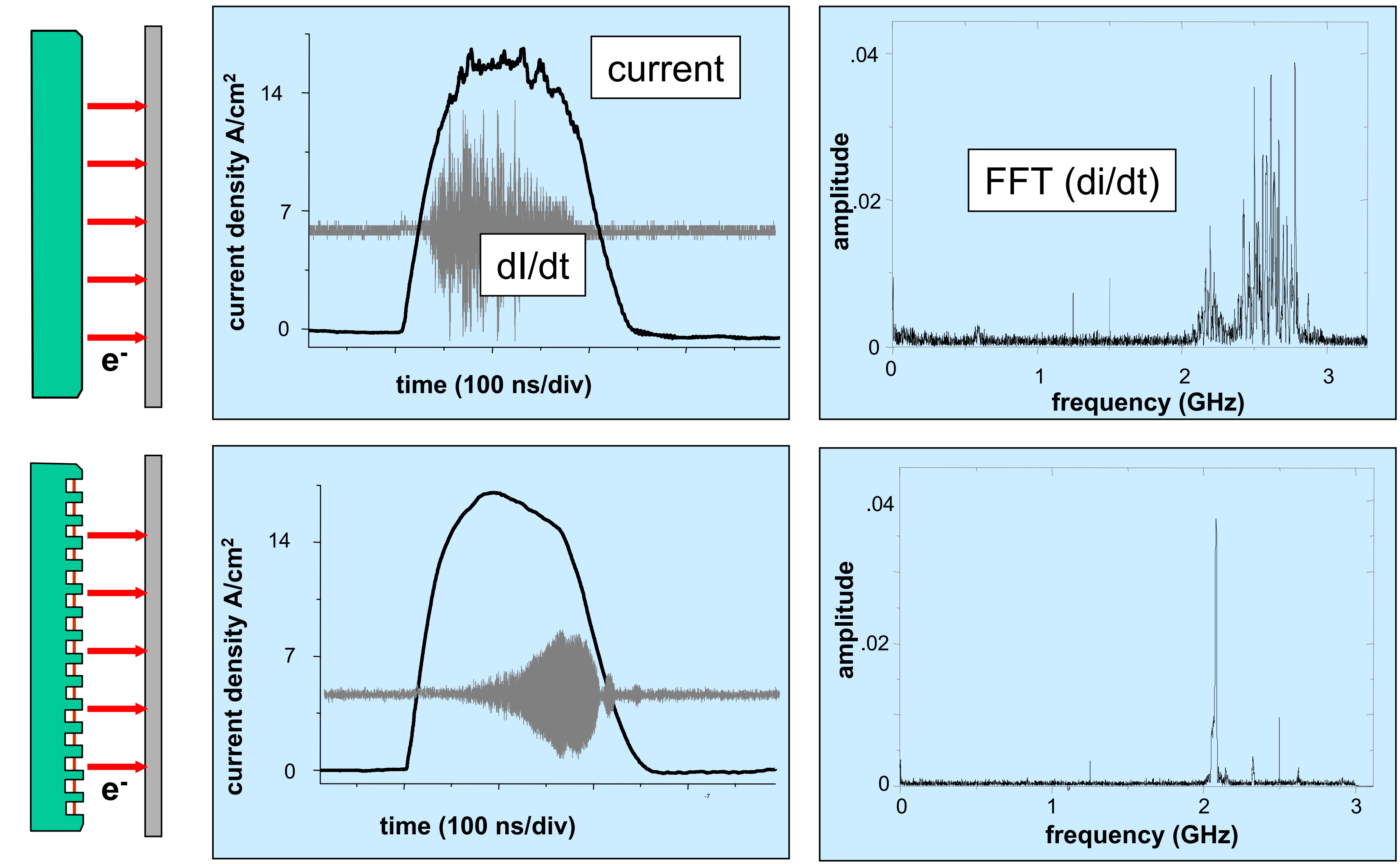



M. Friedman, et al et al Appl. Phys. Lett. **77,** 1053 (2000)

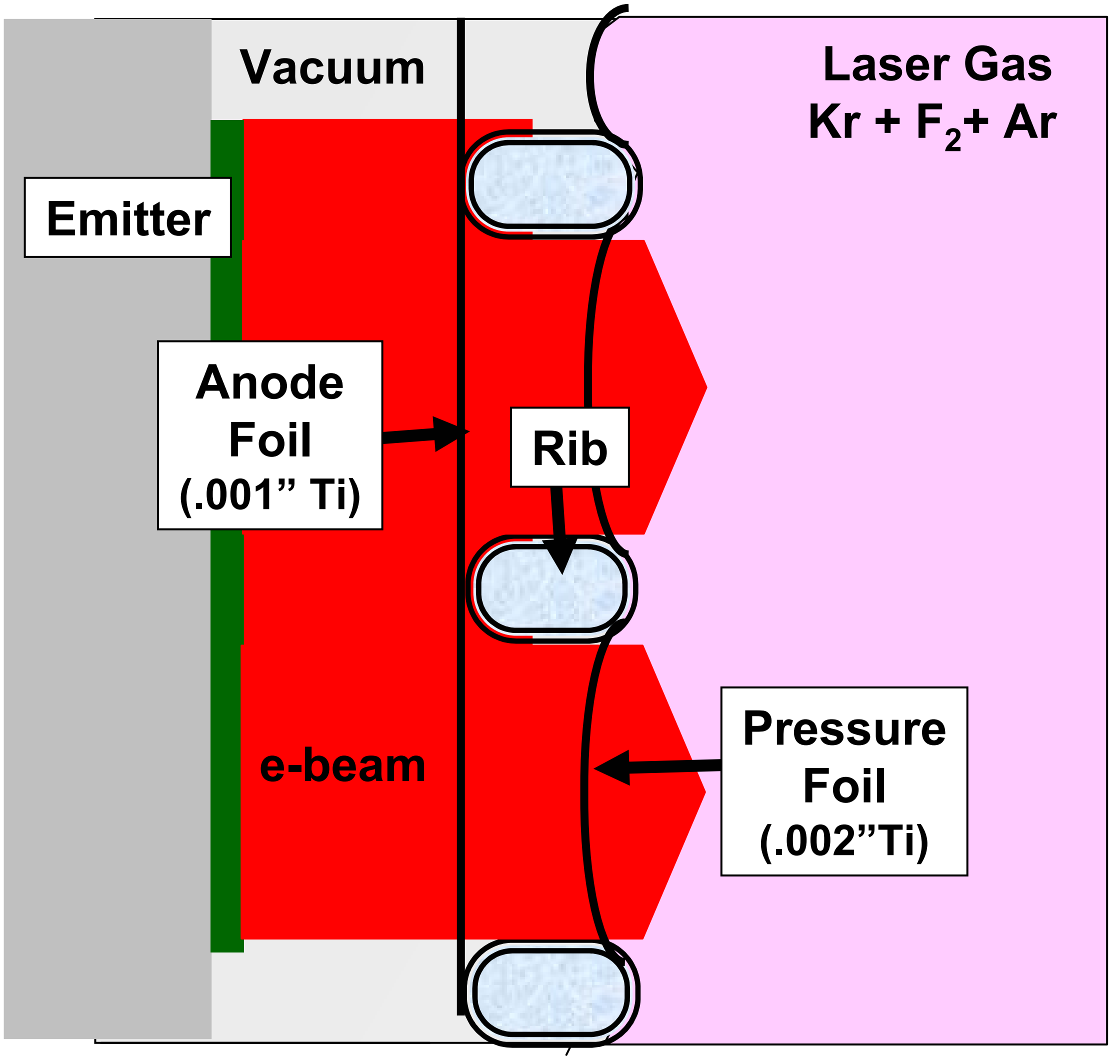
# *Slotting cathode reduces transit-time instability on Nike 60 cm Amplifier*




**Adding Resistors or slotting cathode in other direction is expected to eliminate instability**

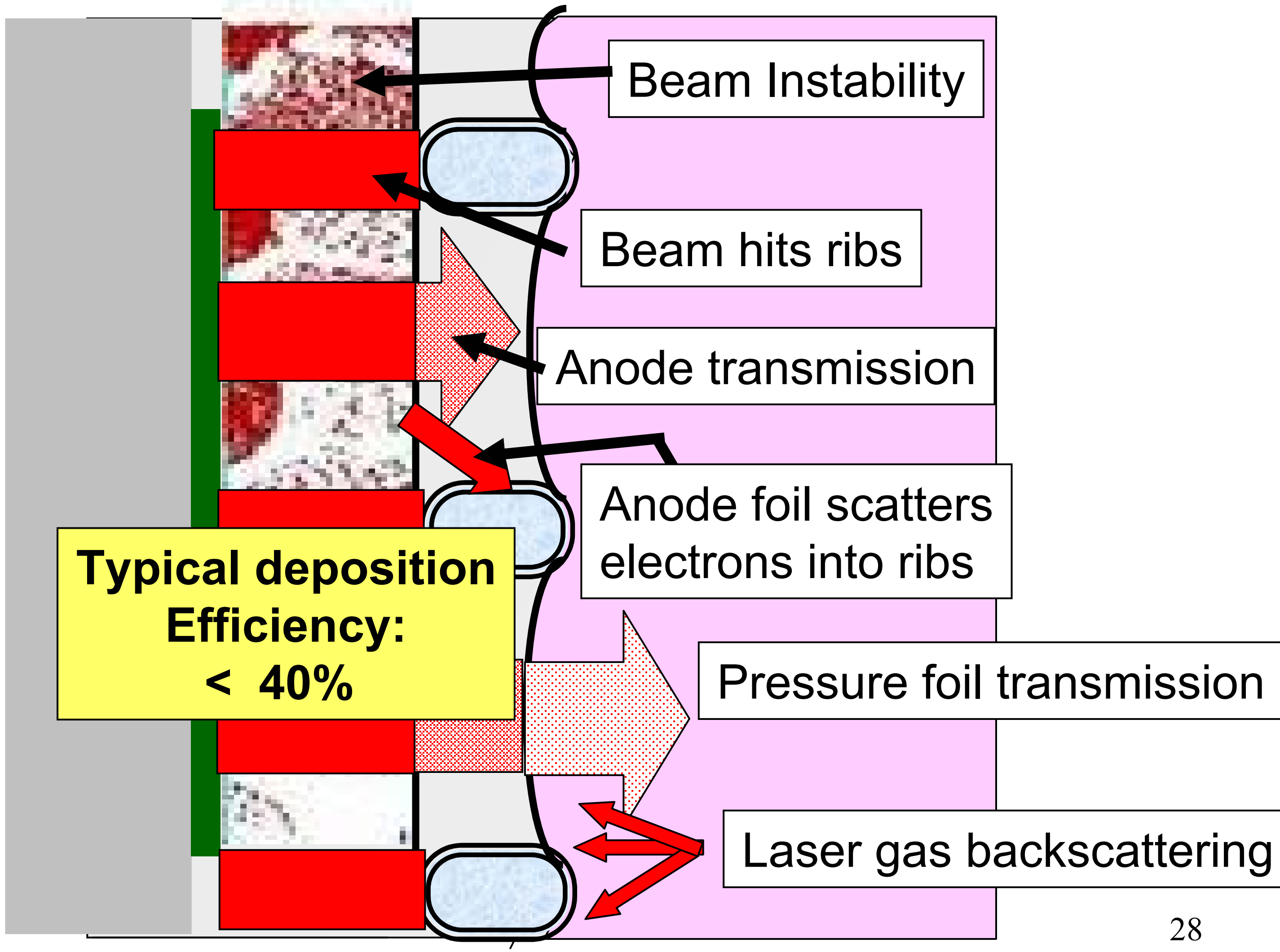
M. Friedman, S.B. Swanekamp, et al Appl. Phys. Lett. **81,** 1597 (2002)

# “Conventional” Cathode/Hibachi: monolithic cathode, anode foil, ribs, + pressure foil…



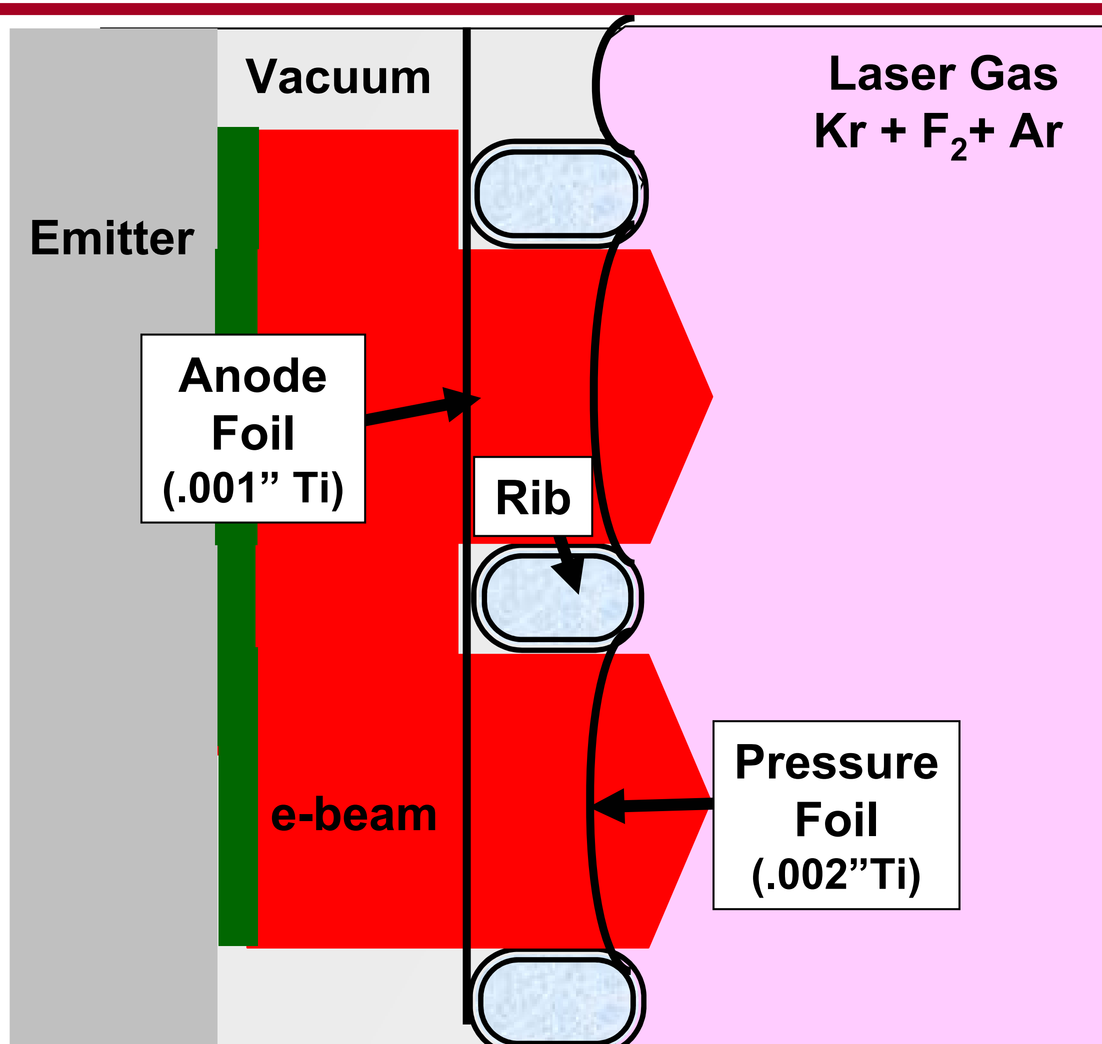
# "Conventional" Cathode/Hibachi: monolithic cathode, a smooth anode, ribs, + pressure foil…

**…..and lots of losses**



# Two innovations allowed high hibachi transmission:

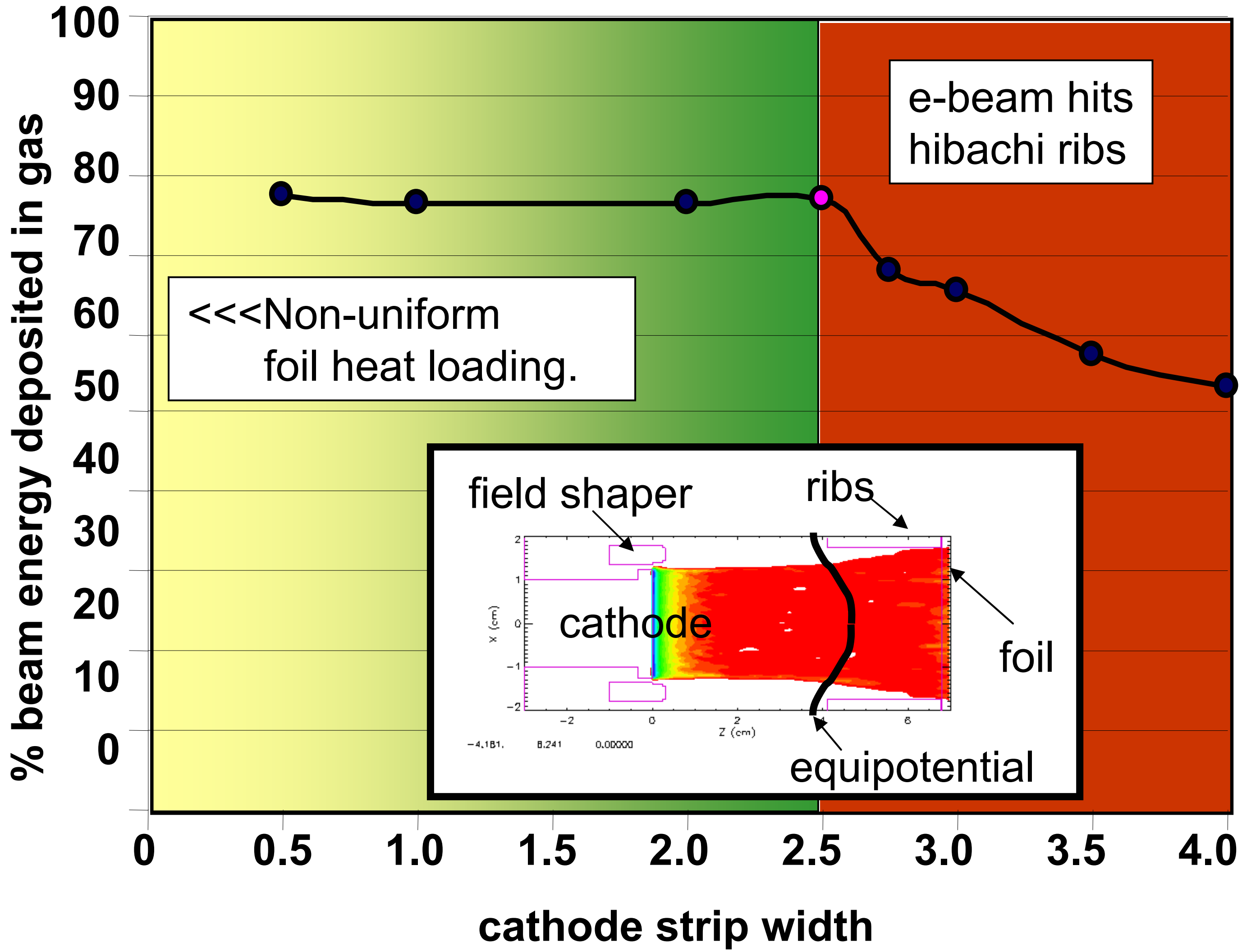
1. Eliminate anode foil
2. Pattern the beam to “miss” the ribs




ISSUES

1. **Non-uniform electric field at anode causes beam spreading**
2. **Beam rotates and skews between cathode and anode due to $B_z$**

# LSP modeling prescribes cathode width needed to accommodate beam spreading

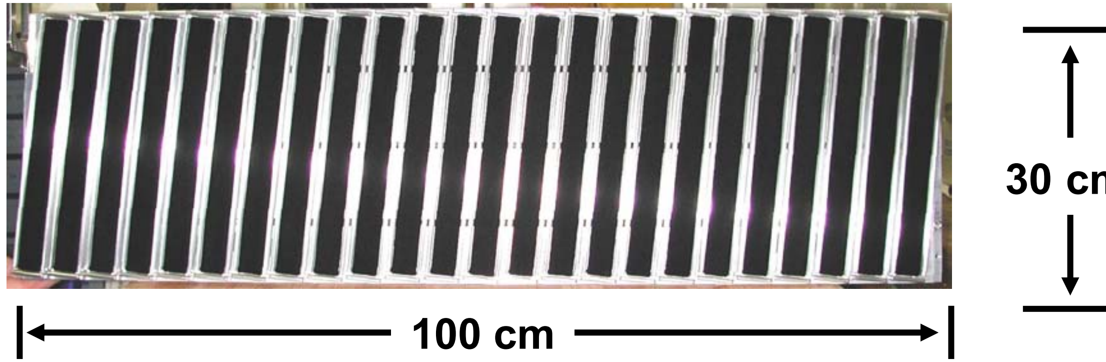




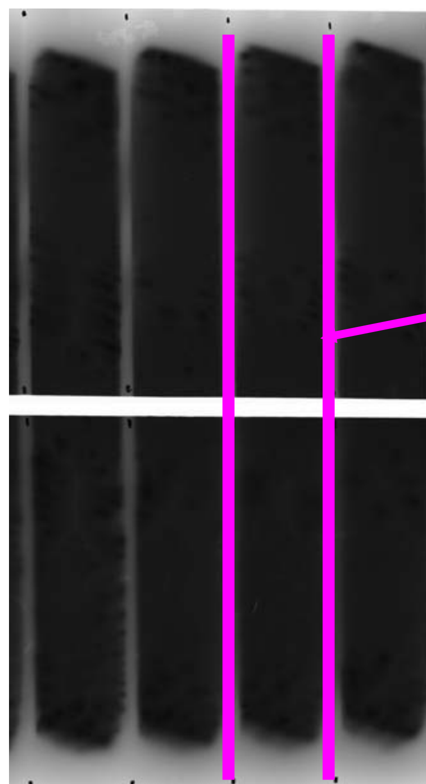

Simulations by D. Rose & D. Welch, MRC Albuquerque

# We can counter-rotate the emitter strips so beam goes straight through the hibachi ribs

Cathode strips rotated 6 degrees



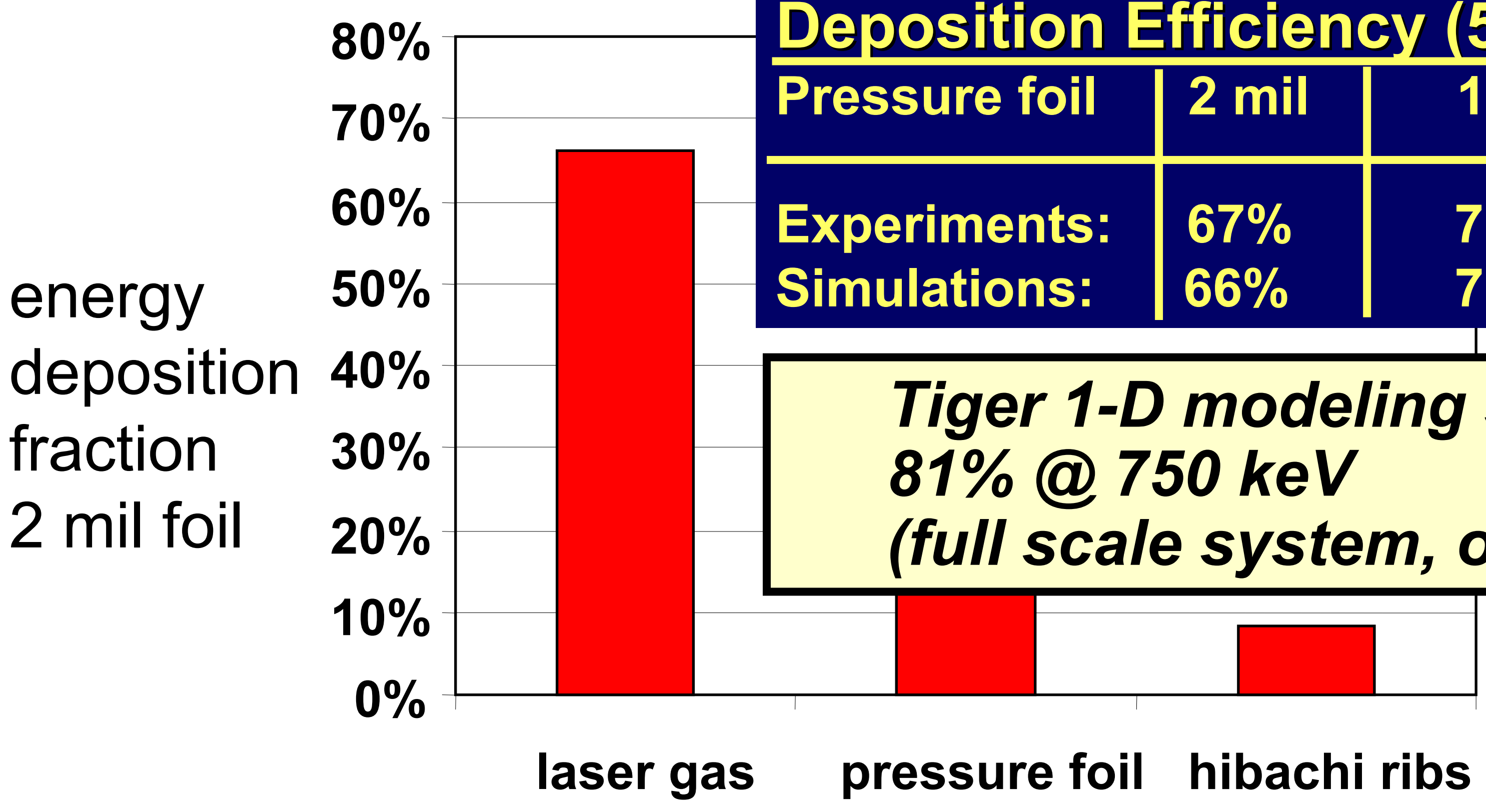

Radiachromic Film:
Time integrated current profile at the pressure foil



Position of the hibachi ribs

# 3-D LSP Simulations (MRC/Albuquerque)

- Prescribe the cathode rotation
- Predict observed electron beam deposition into the gas




**Deposition Efficiency (500 keV):**

| Pressure foil | 2 mil | 1 mil |
|---|---|---|
| Experiments: | 67% | 75% |
| Simulations: | 66% | 76% |

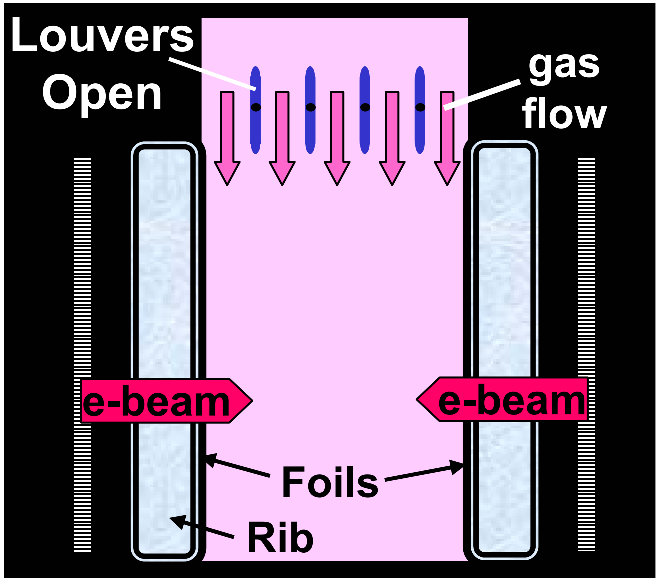
***Tiger 1-D modeling shows 81% @ 750 keV (full scale system, or Nike)***

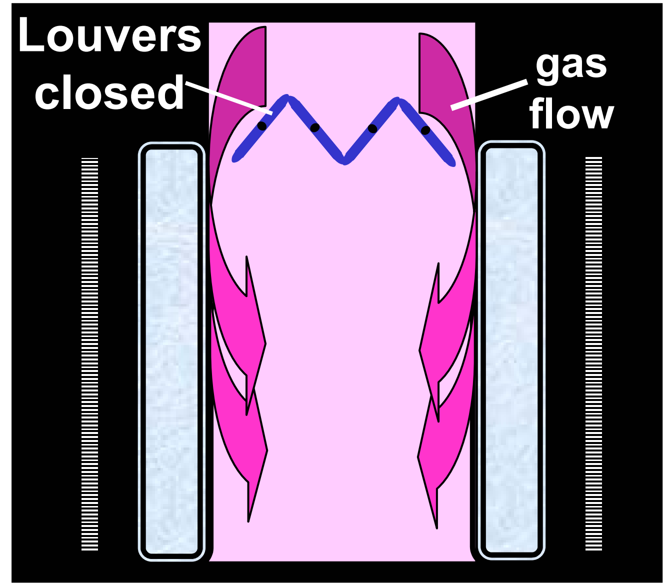
**Efficiency ≡ Energy deposited in laser gas/energy in diode (for flat top portion of beam)**



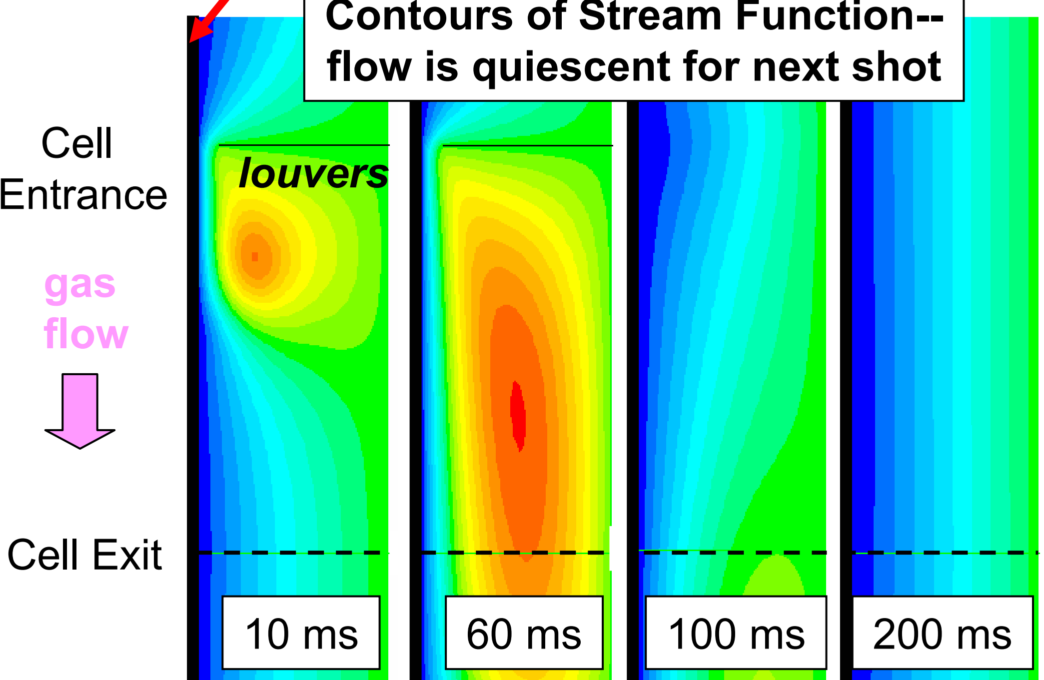
Simulations by D. Rose & D. Welch, MRC Albuquerque

# The recirculating laser gas can be used to cool the Hibachi

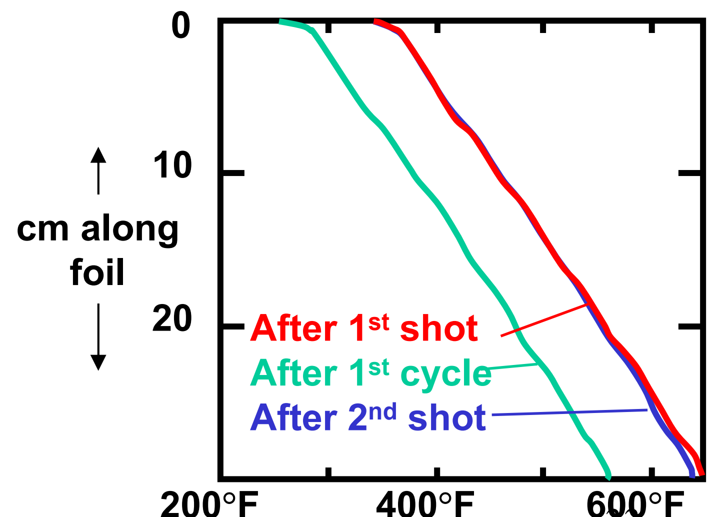



**Contours of Stream Function-- flow is quiescent for next shot**

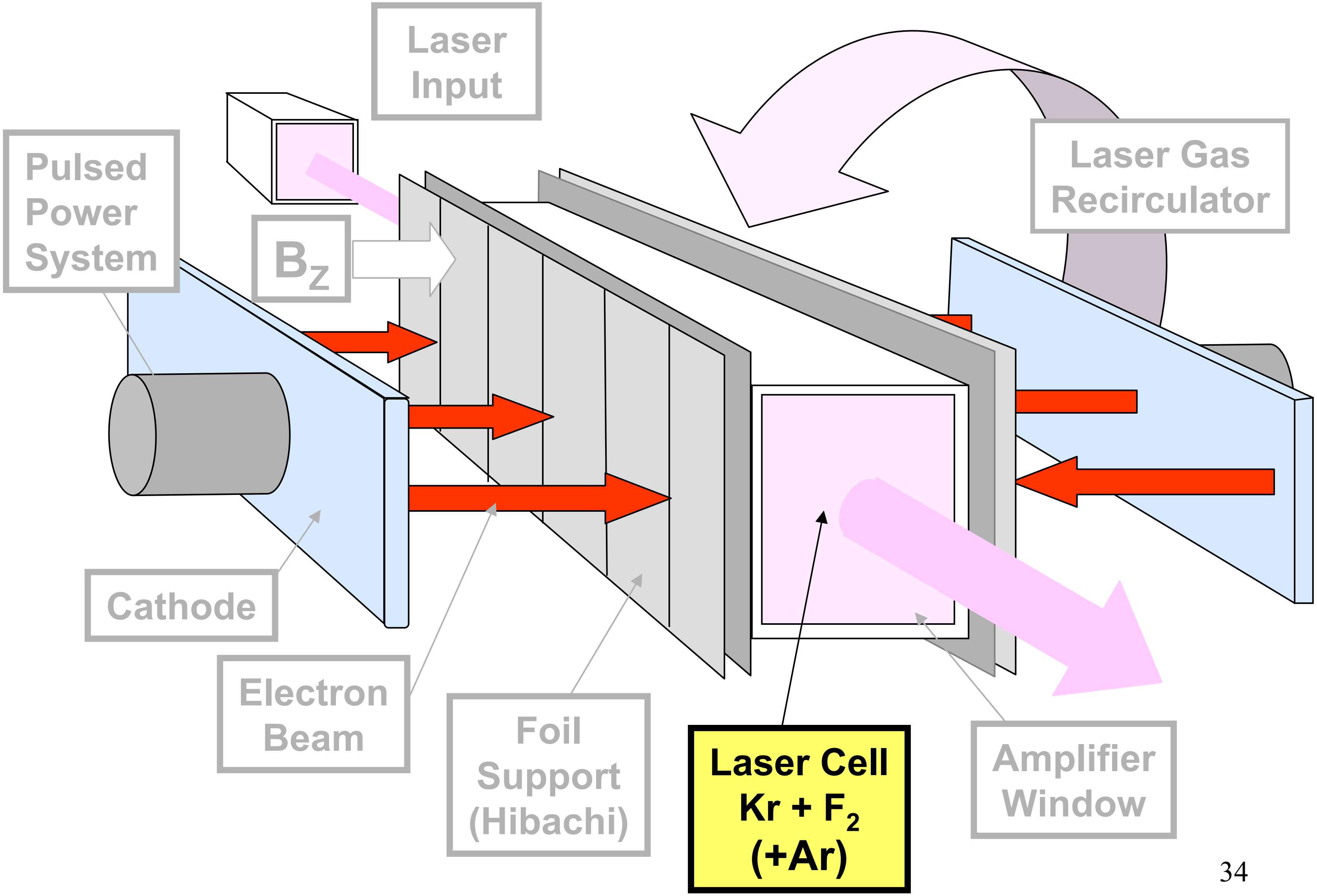



**Foil Temperature below required 650°F**




Concept & Modeling:
A.Banka & J.Mansfield, Airflow Sciences, Inc

# KrF physics



Laser Input
Pulsed Power System
$B_z$
Laser Gas Recirculator
Cathode
Electron Beam
Foil Support (Hibachi)
Laser Cell
$Kr + F_2$
(+Ar)
Amplifier Window

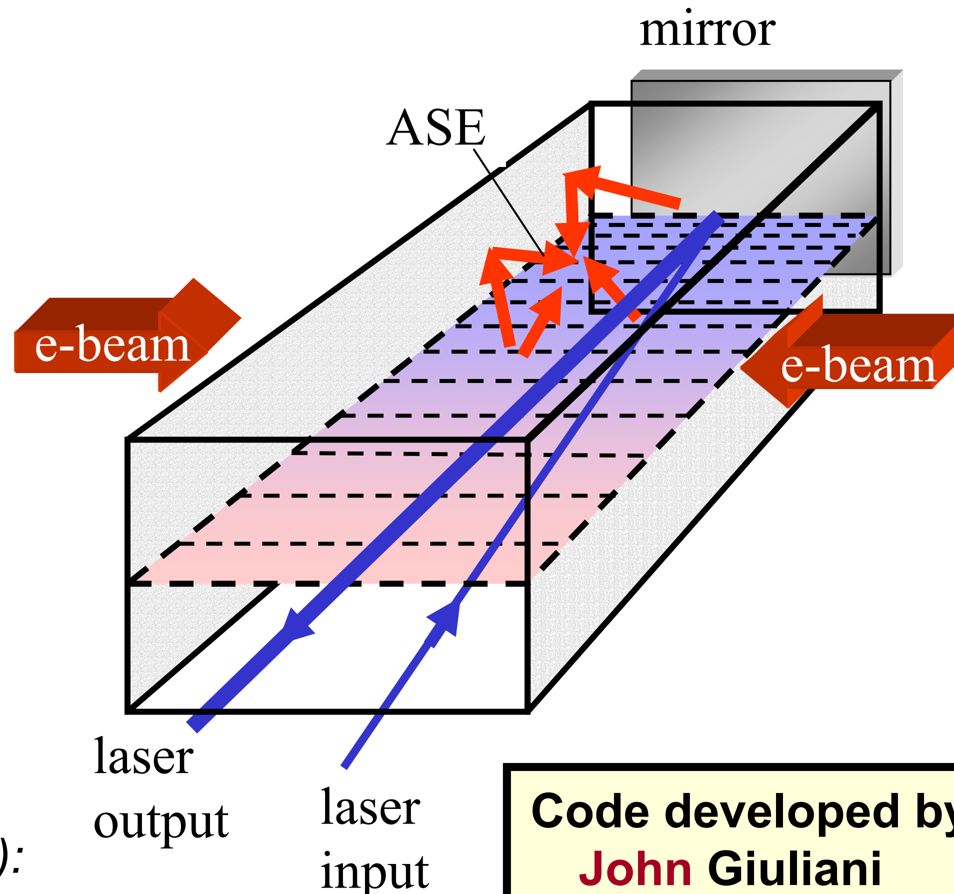
# “Orestes”:
## *Combines relevant physics into a single KrF Physics code*

***electron beam:***
ionization and excitation from
Boltzman analysis

***plasma:***
1D axially resolved, separate
electron and gas temperatures

***kinetics:***
24 species, 122 reactions
includes KrF vibrational structure

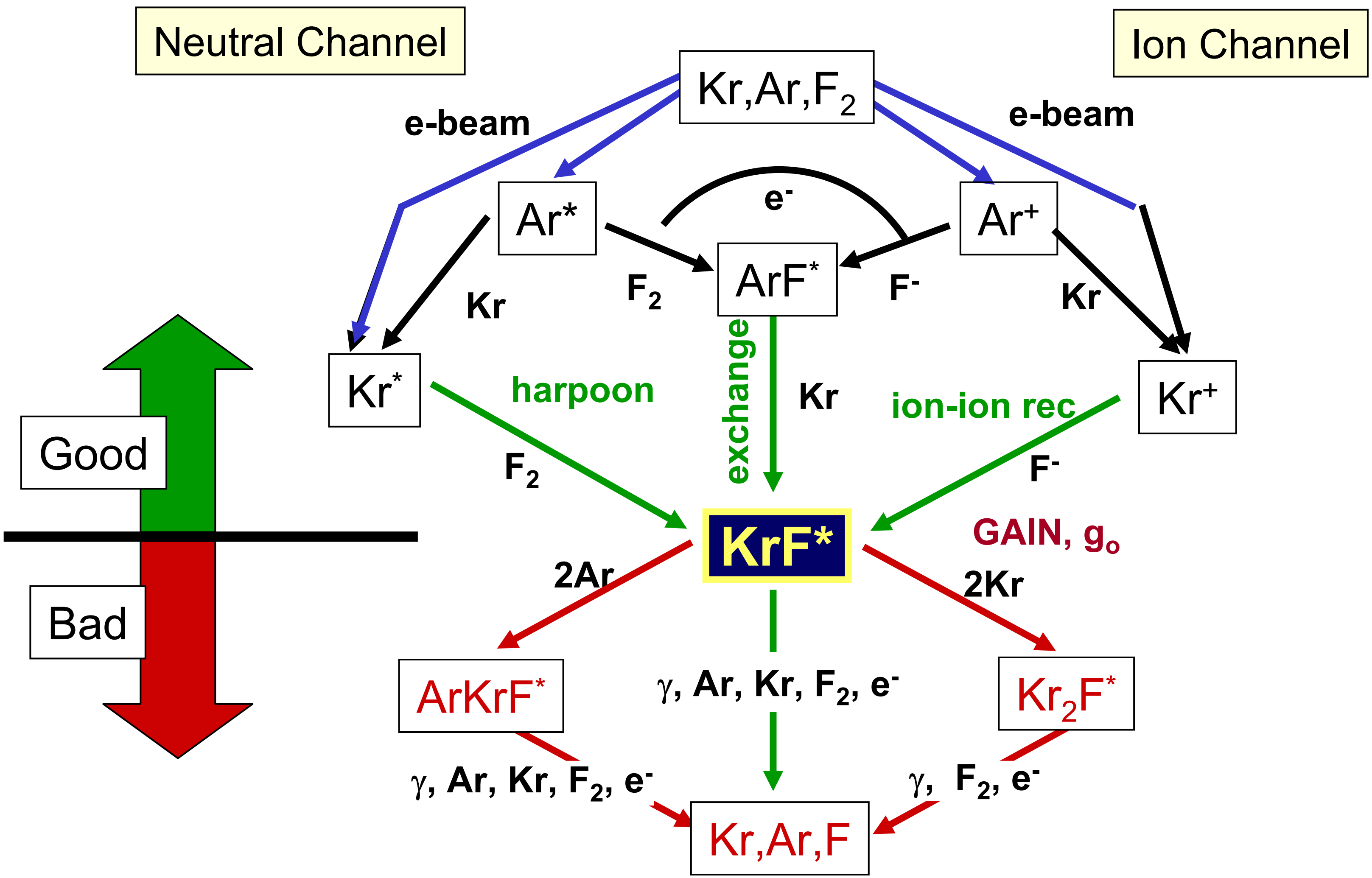
***lasing and ASE:***
*(Amplified Spontaneous Emission):*
3D, time dependent,
ASE gain narrowing




**Code developed by:**
**John Giuliani**
**Paul Kepple**
**George Petrov**
**Bob Lehmberg**

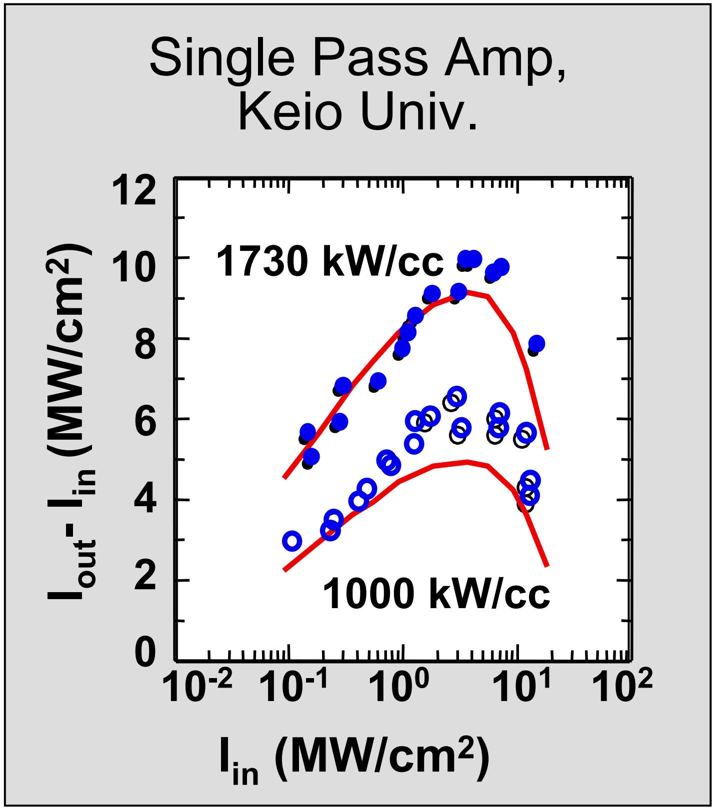
# *KrF Kinetics is a complex process*

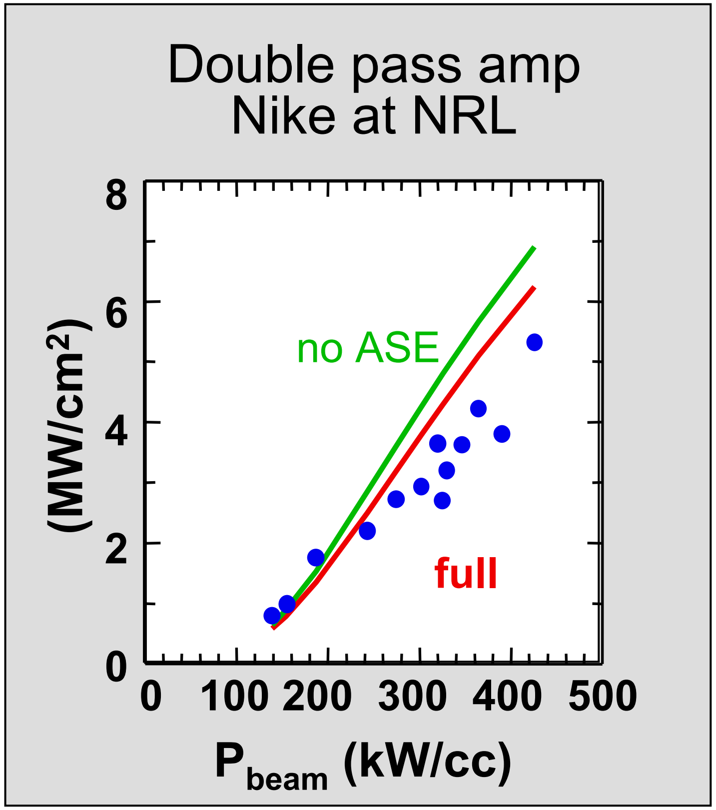
24 species, 122 reactions



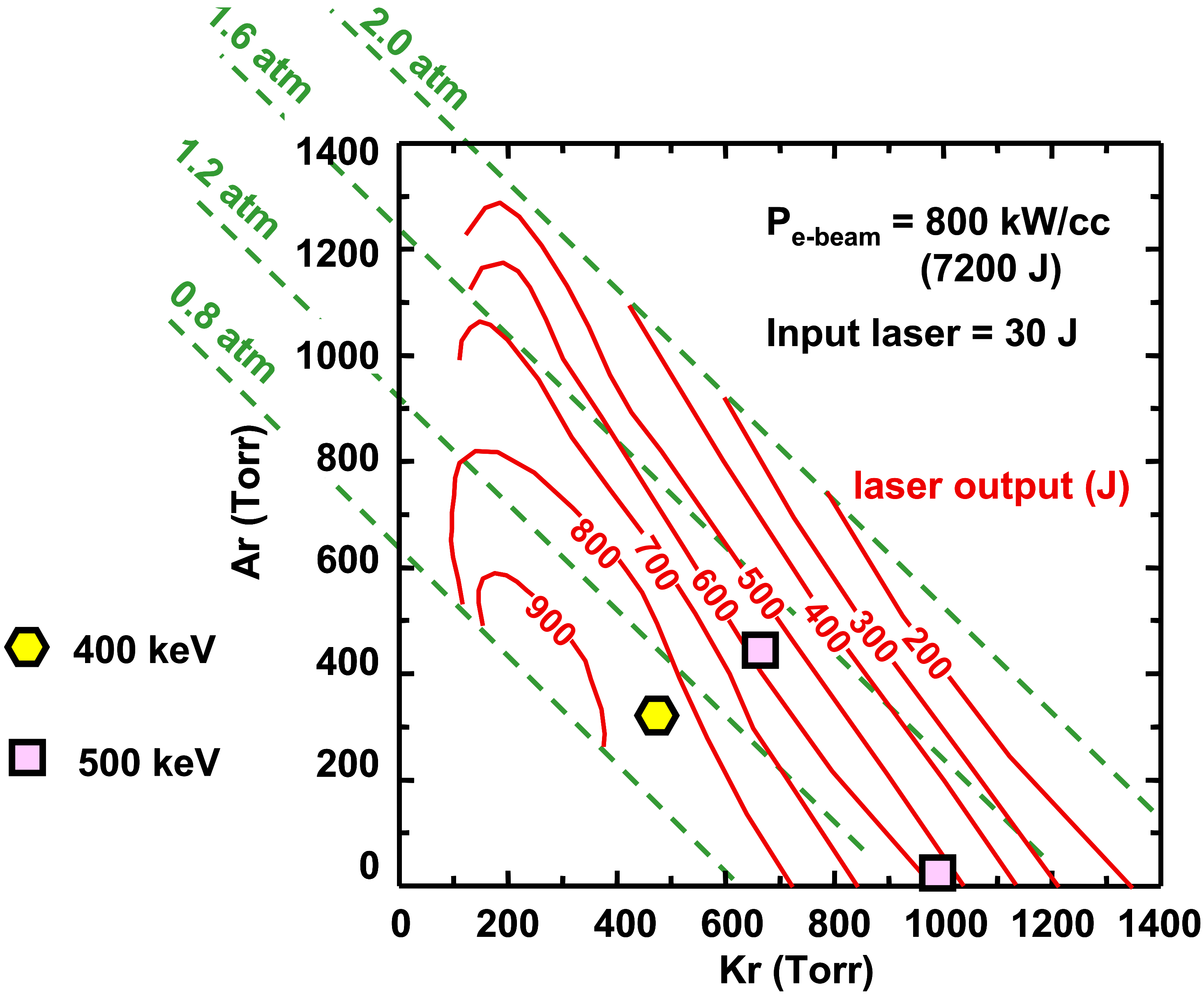

**absorption,** $\sigma = \sigma_{F2}\eta_{F2} + \sigma_{F-}\eta_{F-} + \sigma_{KrF2}\,\eta_{KrF2} + \sigma_{ArF2}\,\eta_{ArF2}$

# Orestes predicts KrF Laser yields under a wide range of operating conditions

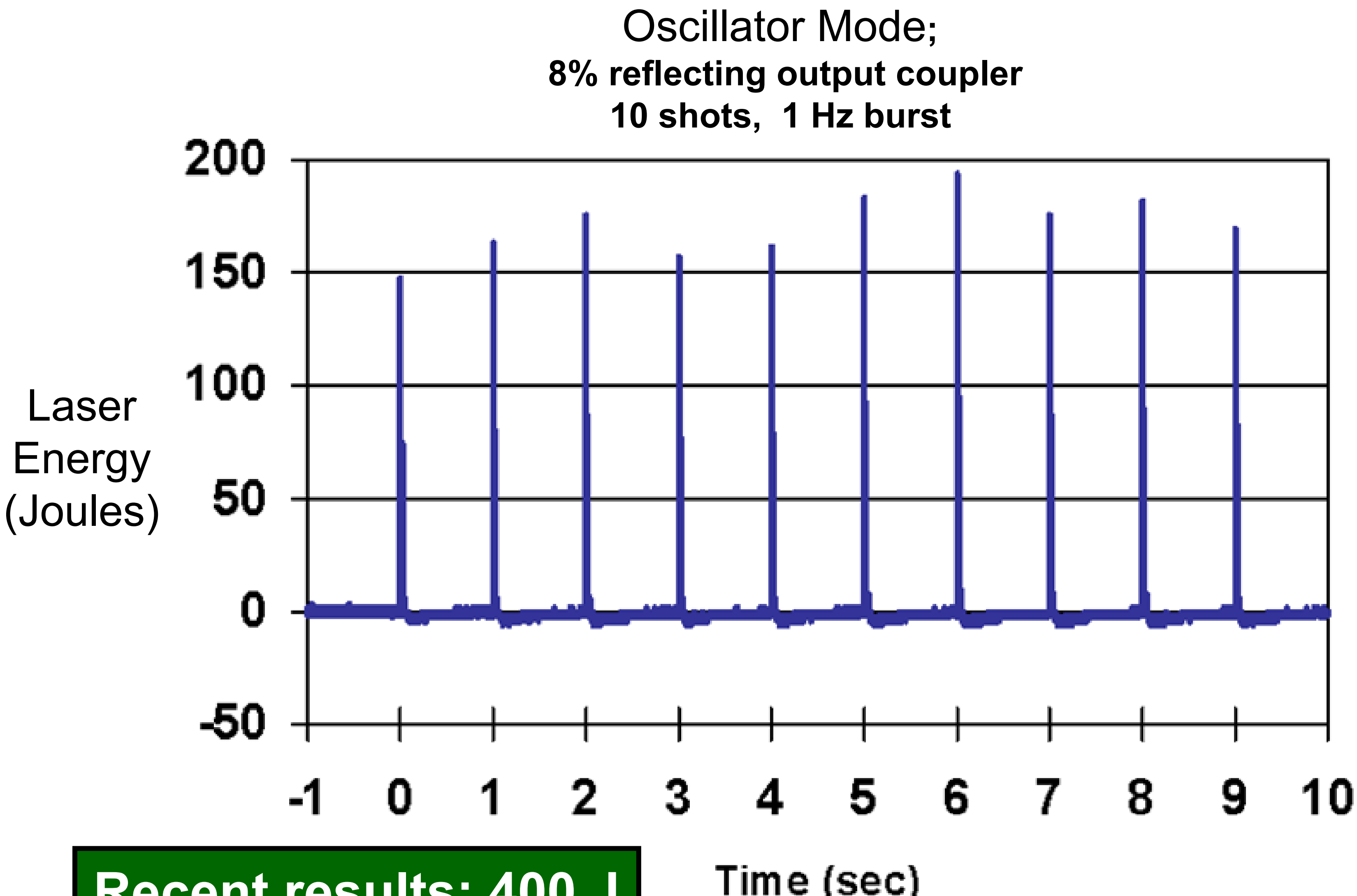


# ORESTES prediction of Electra performance

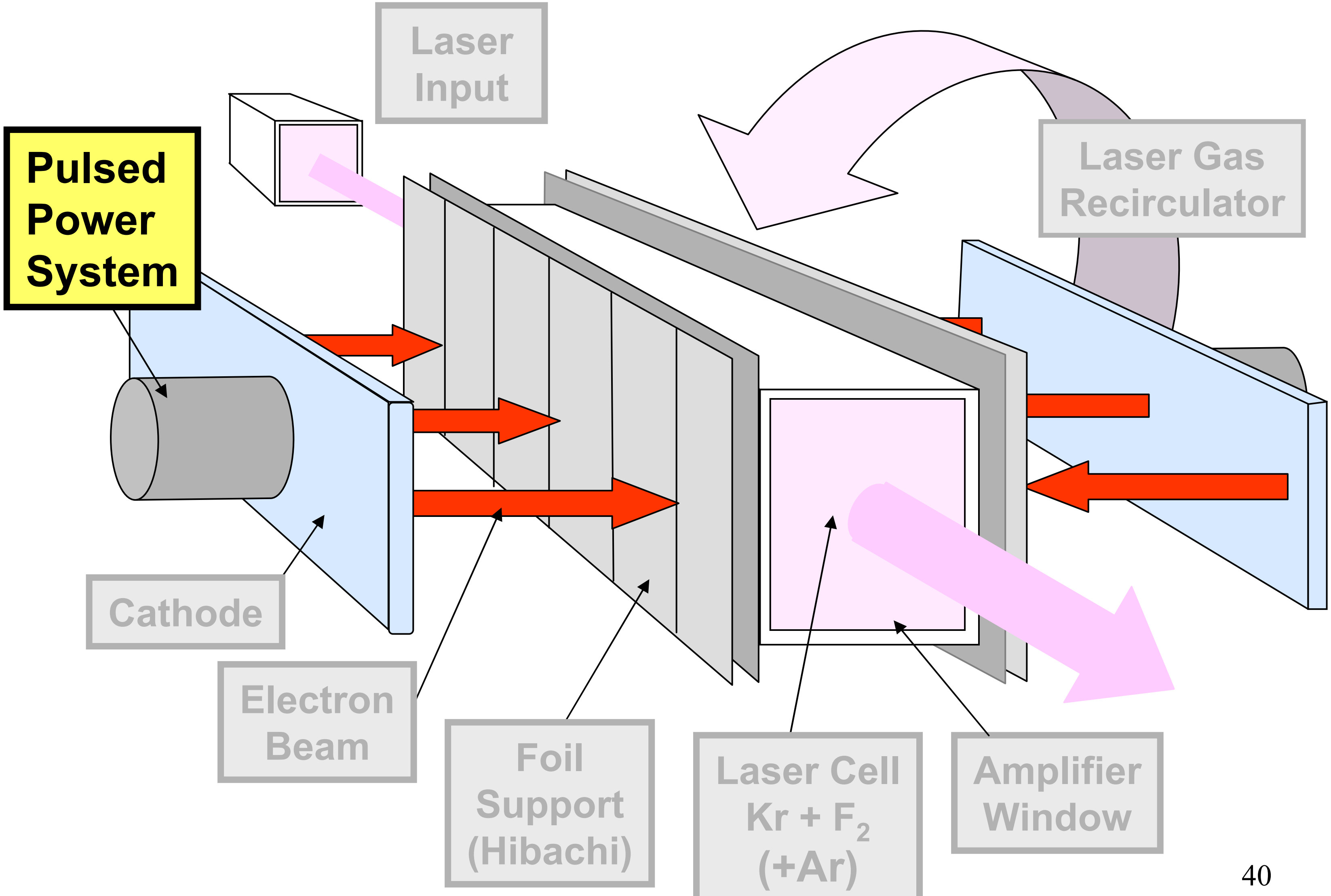


# *The Electra KrF Laser has achieved first light*



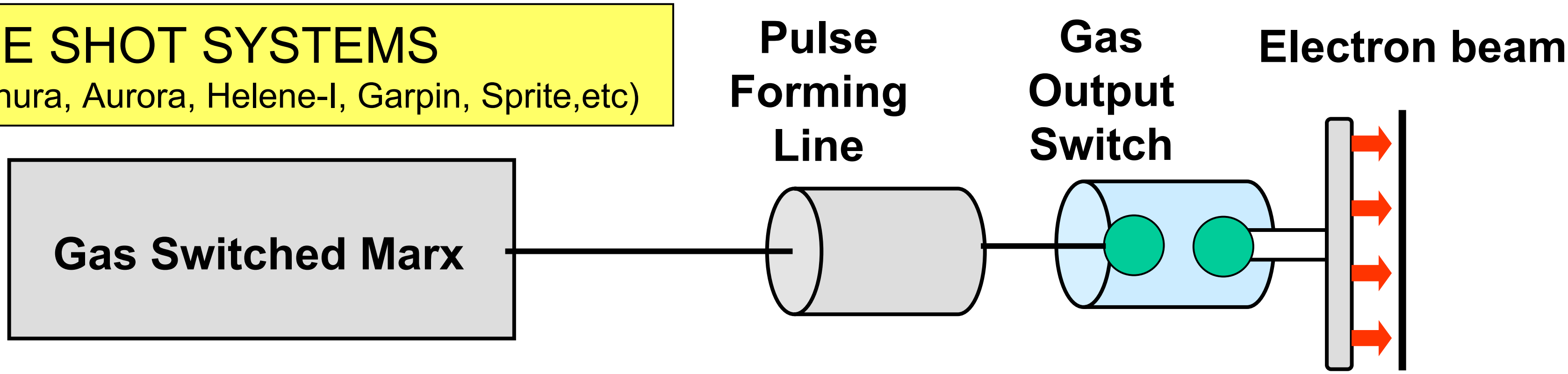

**Recent results: 400 J**

# Pulsed Power

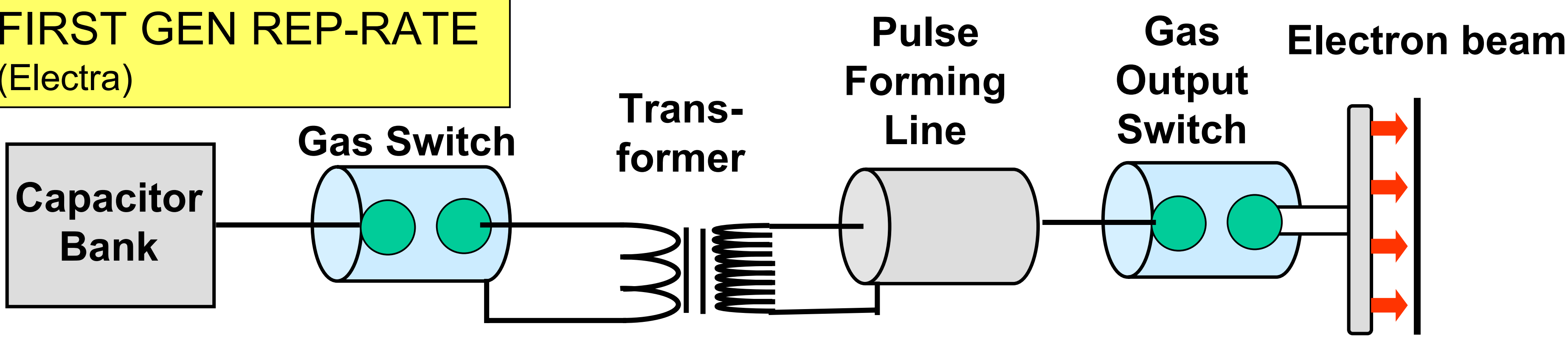


# Evolution of pulsed power for KrF lasers

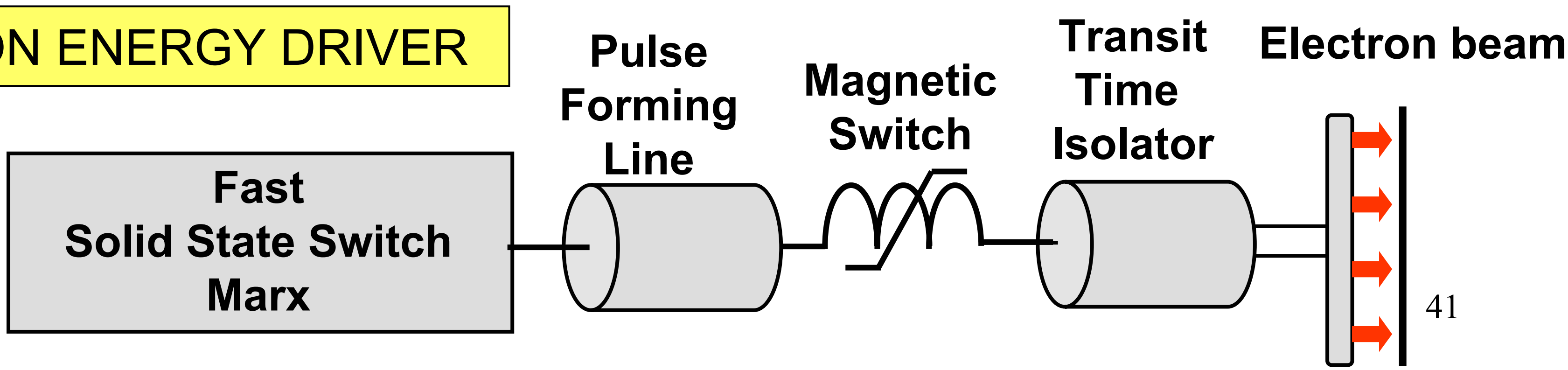
**SINGLE SHOT SYSTEMS**
(Nike, Ashura, Aurora, Helene-I, Garpin, Sprite,etc)




**FIRST GEN REP-RATE**
(Electra)




**FUSION ENERGY DRIVER**



# *Advanced Laser Gated and Pumped Thyristor*

Flood entire switch volume with photons….

> *fast switching times: ~ 100 nsec*

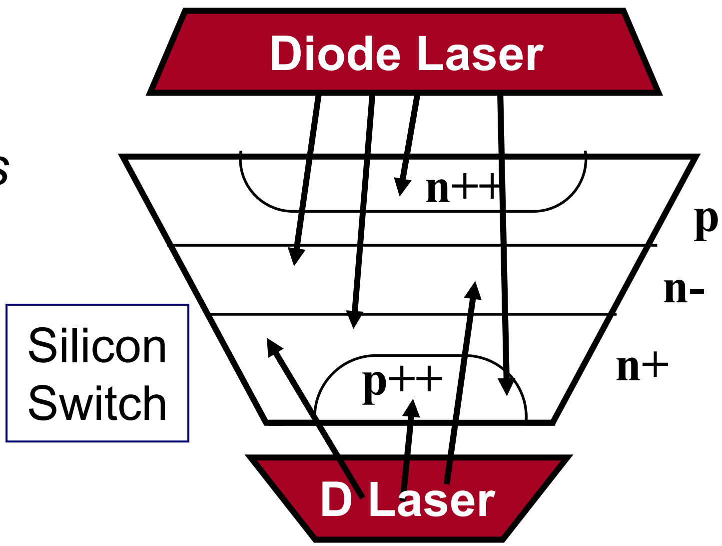
> *Reduces number of compression stages*

Continuous laser pumping reduces losses

> *efficient*

Four junction device

> *enables ~20 kV working devices*




**Demonstrated 1st generation**
**3.2 kV, 2.7 kA/cm$^2$, 5 Hz**
**based on standard switch**

**Tested 2nd generation**
**15.2 kV**
**advanced construction**

# Main points of the talk

## What is a KrF Laser?

Electron beam pumped gas laser

## KrF Lasers and Inertial Fusion Energy

Strengths: Beam uniformity, zooming, cost, scale to large systems

R&D required: efficiency and durability

## The Physics and Technologies of KrF Lasers

Electron beam propagation, transport, and deposition

KrF Kinetics

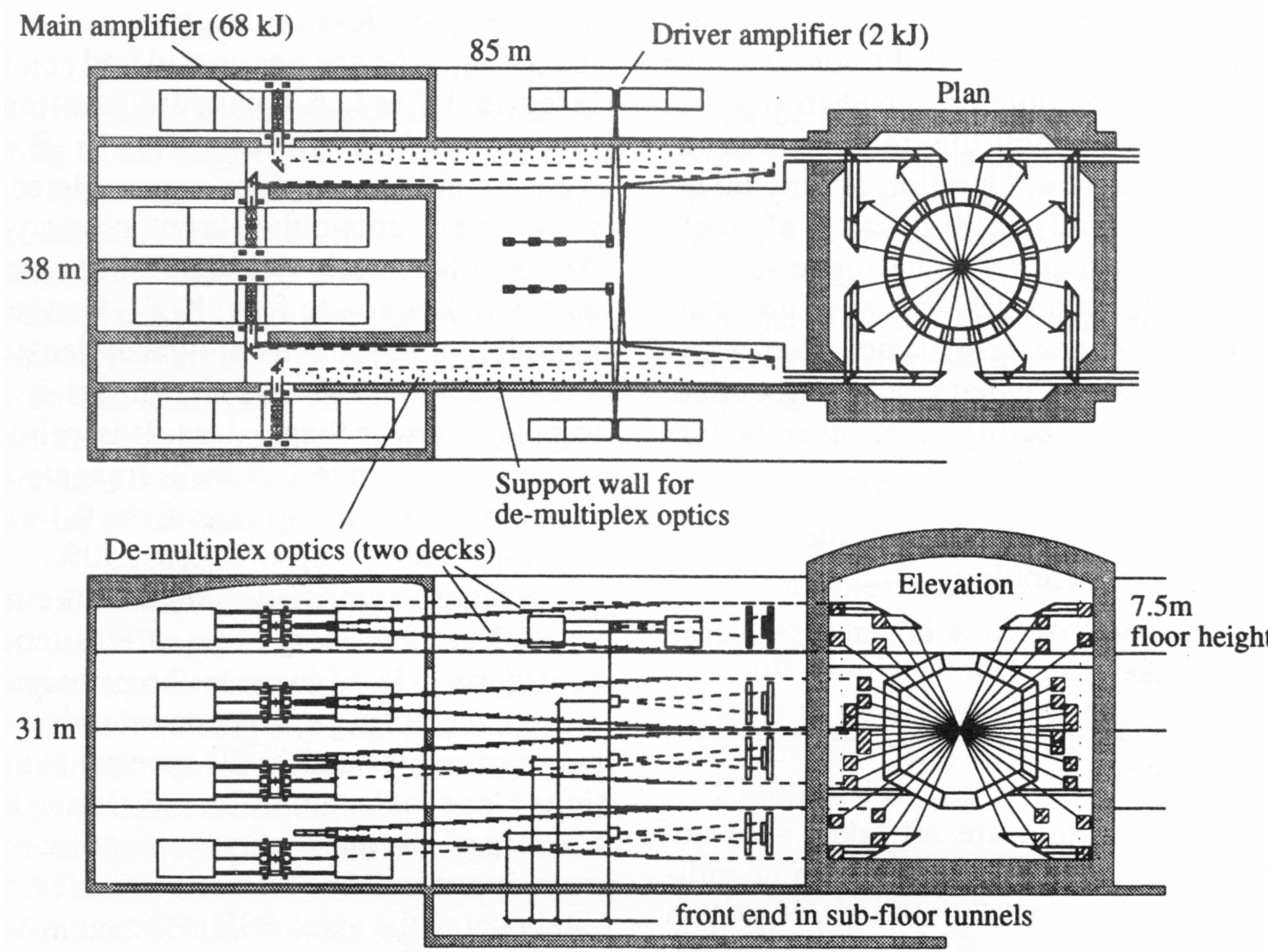
Pulsed Power

## Phased program to develop a KrF Fusion Driver

Part of an integrated program to develop laser fusion energy

# A generalized picture of a KrF Laser fusion power plant

M.W. McGeoch et al Fusion Technology, **32,** 610 (1997)



# A 60 kJ Amplifier

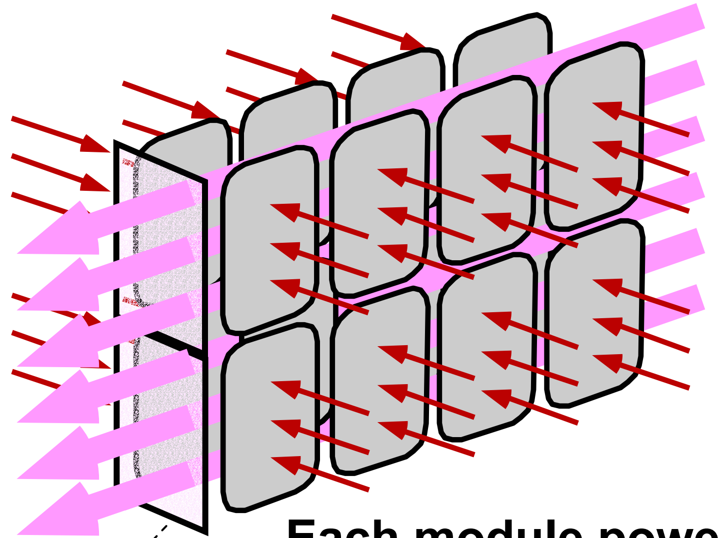
$E_{stored}$ 100 kJ x 8 = 800 kJ

V, I, $\tau$: 800 keV, 84 kA x 16, 600 ns

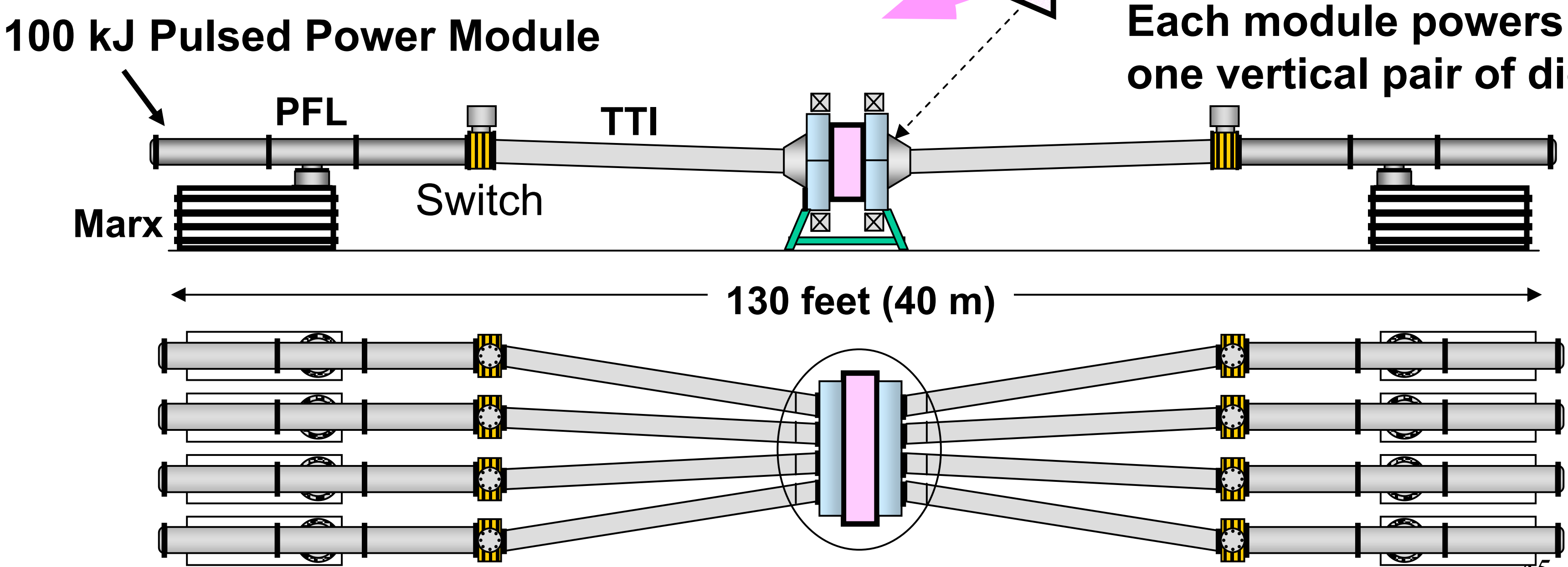
**Energy in gas: 544 kJ**

**Laser Input: 4 kJ**

**Laser Output: 57.8 kJ ($\eta$ = 10.8%)**



**Each module powers one vertical pair of diodes**

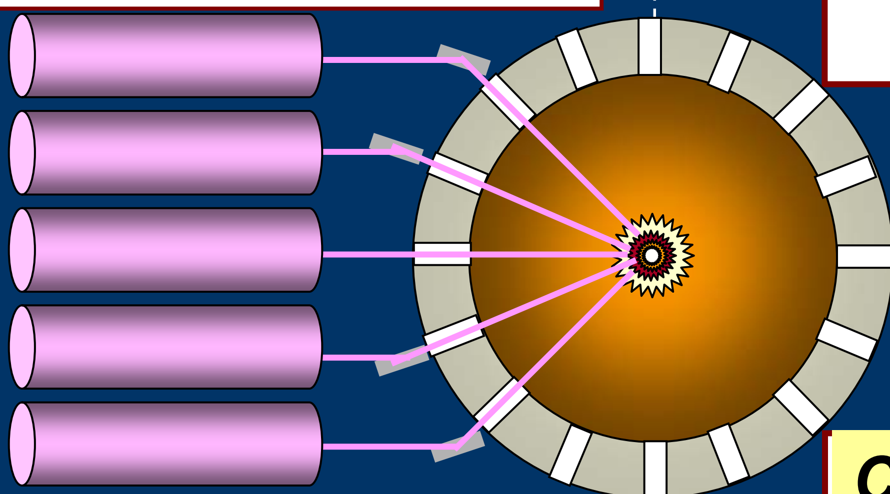


**KrF Laser Development is part of a coordinated National Program to develop Laser IFE as an integrated system.**
**( 8 Government labs, 7 Universities, 8 Private Industries)**

## *Lasers*

**KrF: NRL**
Titan PSD, SAIC, PPPL, Georgia Tech, Commonwealth Tech
**DPSSL: LLNL**
Crystal Systems, Litton, Onyx Corp, Northrup, UR/LLE

*Target factory*



## *Target Fabrication*

GA: Fab, charac, mass production
LANL: Adv foams
SCHAFER: DvB foams

## *Target Injection*

GA: Injector, Injection & Tracking
LANL: DT mech prop, thermal resp.

## *Direct Drive Target Design*

NRL- Target design
LLNL: Yield spectrum, design

## *Chambers and Materials*

WISCONSIN: Yield spectrum / Chambers
LLNL: Alt chamber concepts, materials
UCSD/ANL/INEEL: Chamber dynamics
SNL: Materials response x-rays/ions
ORNL/UCLA/UCSB/Wisconsin: Materials

## *Final Optics*

LLNL: X-rays, ions, neutrons
UCSD: Laser, debris mitigation

# A phased program to develop Laser Fusion Energy

**IFE DEMO**

- ***Demonstrate useable electrical power from Fusion***

**Phase III**

**Engineering Test Facility**

start ~2014-16, operating ~ 2022

- ***2-3 MJ, 60 laser beam lines***
- ***High gain target implosions***
- ***Optimize materials & components.***
- ***~ 300 MW electricity (burst mode)***

**Phase II**

**Integrated Research Experiments and more**

start ~2006

***Establish:***

***Target physics***
***Full scale Laser technology***
***Target Mass Production***
***Injection/tracking in Chamber***
***Final Optics***
***Power Plant design***

**Phase I:**

**Science and technology**

Start 1999

***Develop Viable:***

***Scalable Laser Technologies***
***Target designs***
***Target fab/ injection***
***Final optics***
***Chamber Concept***

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